EMERGY EVALUATIONS OF AND LIMITS TO FOREST PRODUCTION

By

STEVEN JAMES DOHERTY

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1995

UNIVERSITY OF FLORIDA LIBRARIES

We are the sum of all the moments of our lives--all that is ours is in them: we cannot escape or conceal it.

Thomas Wolfe, *Look Homeward Angel*

You can feel the anger in water behind a dam.

Barry Lopez, *River Notes: The Dance of Herons*

ACKNOWLEDGEMENTS

I am grateful to my committee members, Drs. H.T. Odum, J.J. Delfino, C.F. Kiker, B.L. Capehart, and M.T. Brown for their support and encouragement throughout my graduate studies. Dr. F.N. Scatena, research hydrologist with the International Institute of Tropical Forestry was an adjunct faculty member and oversaw my studies in Puerto Rico. Professor Per Olof Nilsson, professor with the Swedish University of Agricultural Sciences in Garpenberg, as an unofficial member, supervised my studies in Sweden. My chairperson, Dr. Odum, reintroduced the physical and biological world around me with his energy systems approach, widening my world view and redirecting my role as a scientist and planner. Dr. Brown has been an advisor, collaborator and friend, a combination never too common in universities.

Funding in Sweden was provided by the Swedish University of Agricultural Sciences, Garpenberg, on a grant from Vattenfall, the Swedish State Power Board, Project no. 5719-65-312, *Energy Evaluation of Forest Systems*, P.O. Nilsson, supervisor. The Swedish Royal Academy of Sciences also provided direct and indirect support. Studies in Puerto Rico were funded by a contract between the Institute of Tropical Forestry, Southern Forest Experiment Station, USDA Forest Service and the Center for Environmental Policy at the University of Florida, H.T. Odum, Principal Investigator, project 19-93-023, *Forest Product Value and Energy*. Work in Puerto Rico was aided directly and indirectly by the Luquillo Long Term Ecological Research

Project of the National Science Foundation, Robert Waide and Ariel Lugo, Principal Investigators.

Many aides and courtesies were provided by staff of the International Institute of Tropical Forestry: Dr. Ariel Lugo, Samuel Moya, Dr. Whendee Silver, Dr. John Parrotta, Elizabeth Trevino, and Sylvia DeCastro. Ulf Sundberg, B-O Danielsson, Jan Erik Mattsson, Jörgen Marks and Kerstin Tordmar of the Department of Operational Efficiency in Garpenberg, Torbjörn Rydberg from the Department of Crop Production Science in Uppsala, and A-M Jansson, Carl Folke and Monica Hammer with the Systems Ecology Group at Stockholm University provided valuable input and participated in discussions and seminars. Opportunity to continue energy studies was provided by Dr. R.H. Richardson, Professor with the Department of Zoology, during my two years with the University of Texas at Austin.

Bo Hektor participated in initial evaluations of electricity options for Thailand. Naser Altibi and Berdell Knoles from Gainesville Regional Utilities provided input for evaluations of electric generating stations in Gainesville, Florida. I acknowledge the help of students and staff in the Systems Ecology program, Department of Environmental Engineering Sciences, and Center for Environmental Policy, especially Robert Woithe and Joan Breeze. Finally I would like to acknowledge Sandra, Ulanda, and Alikai for providing joy and purpose for the completion of this dissertation.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii

LIST OF TABLES vii

LIST OF FIGURES x

ABSTRACT xiv

INTRODUCTION 1

- Issues and Research Objectives 2
- Energy Systems Language 5
- Concepts and Definitions 6
  - General Systems Principles 6
  - Indices of Resource Use, Efficiency and Exchange 16
- Review of Literature on Energy Analyses and Biomass Yields 20
  - Limits to Biomass Production 20
  - A Short History of Net Energy Analysis 25
  - Previous Net Energy Studies of Biomass and Fuels 26
- Forest Systems Evaluated in This Study 30
- Dissertation Plan 36

METHODS 38

- Energy Systems Evaluations 38
  - Energy Systems Diagramming 39
  - Emergy Evaluation Tables 41
- Resource Indices and Synthesis 44
- Computer Simulation 45

RESULTS 46

- Emergy Evaluation of Forest Productivity and Extraction 46
  - Forests of Southern Sweden 46
  - Forests of Southern Illinois 51
  - Slash Pine Forests of Florida 59
  - Secondary Rainforests of Papua New Guinea 66

Emergy Evaluation of Plantation Productivity 66
    Salix Plantations in Sweden 66
    Melaleuca Plantations in South Florida 70
    Siris Plantations in Puerto Rico 78
Emergy Evaluation of Non-market Forest Services 83
    Carbon Sequestration 83
    Reforestation 89
    Regional Water Supply 97
Emergy Evaluation of Forest Economic Uses 101
    Wood Fuels 101
    Pulp and Paper Products 107
    Tourism and Recreation 117
Emergy Evaluation of Electricity Generation 123
    Gainesville Regional Utilities 123
    Electricity Production in Thailand 134
    Wood-fired Electricity Generation 144

DISCUSSION 156

Comparison of Forest Production Systems 156
    Solar Transformities of Agroforest Systems 159
    Emergy Yield Ratio as a Function of Economic Feedback 159
    Optimal Investment for Production and Harvest of Biomass 161
    Thermodynamic Minimum Transformities for Biomass 161
    Emergy Yield and Investments as Functions of Cycle Time 164
Comparison of Electric Power Transformation 166
    Solar Transformities for Primary Fuels and Electricity 166
    Emergy Yield Ratio as a Function of Economic Feedback 169
    Optimal Investments for Primary Fuels and Electricity 171
    Thermodynamic Minimum Transformities for Fuels and Electricity 171
Comparison of Yield and Cycle Time from Forest Alternatives 174
    Emergy Yield and Investment as Functions of Fuelwood Transformation 177
    Energy Yield and Quality as Functions of Cycle Time and Processing . . 181
    Relationship of Area and Tme in Biomass Production 182
Computer Models of Systems Principles 182
    Simulation of Emergy Yield and Cycle Time 182
    Mathematical Relationship of Emergy Yield and Investment Ratios 186
Regional Values 192
    Forest Production and Carbon Sequestration 192
    Regional Water Supply 197
Summary and Conclusions 200

APPENDIX A 202
APPENDIX B 204
LITERATURE CITED 205
BIOGRAPHICAL SKETCH 215

LIST OF TABLES

1. Definitions of central concepts and units 9

2. Solar transformities (*sej*/J), solar emergy per unit mass (*sej*/g), and solar emergy-use per gross economic product (*sej*/$) used in this study to convert resources into common units of solar emergy 12

3. Summary of data characterizing agroforest ecosystems evaluated in this study 31

4. Emergy evaluation of boreal spruce and pine silvicultural forest production and timber extraction under 80 year rotation schedules in southern Sweden . . 47

5. Emergy evaluations of typical loblolly pine and mixed hardwood forest production and timber extraction under different rotation schedules in Shawnee National Forest, southern Illinois 54

6. Emergy evaluation of slash pine silvicultural production and timber extraction under 25 year rotation schedules in north Florida 62

7. Emergy evaluation of secondary rainforest production and timber extraction in New Britain, Papua New Guinea 67

8. Emergy evaluation of willow plantation production and fuelwood harvest under 4 year rotation schedules in southern Sweden 71

9. Emergy evaluation of eucalyptus and melaleuca plantation production and fuelwood harvest under 5 year rotation schedules in south Florida 75

10. Emergy evaluation of siris planation production under 11 year rotation schedules in Puerto Rico 79

11. Emergy evaluation of above ground production and biomass storage in five natural tropical forest ecosystems in Puerto Rico 84

12. Emergy evaluation of possible reforestation in Puerto Rico using plantations as foster ecosystems toward development of a secondary forest 90

13. Emergy evaluation of possible reforestation in Puerto Rico with initial seeding from exotics facilitating natural succession toward a secondary forest 92

14. Annual volume runoff, energy and solar empower for surface water in four forested watersheds of Luquillo Experimental Forest, Puerto Rico 98

15. Emergy evaluation of wood chip production and use as an alternative biomass fuel for a 10 MW district heating facility Sweden 102

16. Emergy evaluation of wood powder production and use as an alternative biomass fuel for a 10 MW district heating facility in Sweden 108

17. Emergy evaluation of recreation in Luquillo Experimental Forest, Puerto Rico 120

18. Emergy evaluation of natural gas-fired electricity production at a 19.5 MW capacity plant in Gainesville, Florida 124

19. Emergy evaluation of natural gas-fired electricity production at a 44 MW capacity plant in Gainesville, Florida 126

20. Emergy evaluation of natural gas-fired electricity production at an 81 MW capacity plant in Gainesville, Florida 128

21. Emergy evaluation of coal-fired electricity production at a 218 MW capacity plant in Gainesville, Florida 130

22. Emergy evaluation of natural gas-fired electricity production in Thailand . . 135

23. Emergy evaluation of coal-fired electricity production in Thailand 137

24. Emergy evaluation of oil-fired electricity production in Thailand 139

25. Emergy evaluation of lignite-fired electricity production in Thailand 141

26. Emergy evaluation of eucalyptus plantation production, fuelwood development and electricity production at a proposed 25 MW capacity plant in Thailand 149

27. Emergy evaluation of wood-fired electricity production in Jari, Brazil 153

28. Summary of measurements calculated from evaluations of agroecosystems 157

29. Summary of measurements calculated from evaluations of electricity generation 168

30. Comparisons of measurements for three agroforest ecosystems under different rotation schedules in Sweden 176

31. Pathway variables, initial conditions, and calibration of transfer coefficients for computer simulation model of biomass production and emergy yield ratio as a function of cycle time 184

32. Emdollar (em$) values for forest production and biomass storage in agroforest ecosystems evaluated in this study 193

33. Emdollar (em$) values for surface water runoff from four forested watersheds in the Luquillo Experimental Forest, Puerto Rico 198

LIST OF FIGURES

1. Systems diagram relating principles of self-organization, maximum power, thermodynamic efficiency and net yield for two paradigms of resource-use: (a) natural, unmanaged ecoystems; (b) managed agroforestry systems 3

2. Symbols and definitions of energy language diagramming used to represent systems 7

3. Energy transformations and hierarchical ordering of ecosystems illustrating the concept of solar emergy: (a) spatial pattern; (b) system network; (c) network aggregation by hierarchical levels; (d) sequential energy flows; and (e) solar transformities 8

4. Calculation of measurements made for resource-conversion systems: (a) solar transformity; (b) emergy ratios of yield and investments; (c) emergy exchange ratio of an economic transaction 14

5. Overview diagram for comparing benefits of a proposed resource-use system with the current one it would replace or with other sectors typical of a region 19

6. Allocation of gross production in different agro-forest systems 22

7. The time-information-energy triangle identifying an output as a trade off between three parameters 24

8. Systems diagram of boreal spruce/pine silvicultural forest production and timber extraction under 80 year rotation schedules in southern Sweden 50

9. Systems diagram of unmanaged forest production in northern coniferous ecosystems of southern Sweden: (a) self-thinned, natural mixed coniferous forest regeneration,100 years old; (b) old growth spruce forest, 200 years old 52

10. Systems diagrams of typical loblolly pine and mixed hardwood silvicultural forest production and timber extraction under different rotation schedules in the Shawnee National Forest, southern Illinois 60

11. Systems diagram of slash pine silvicultural forest production and timber extraction under 25 year rotation schedules in north Florida 65

12. Systems diagram of secondary tropical rainforest production, above ground biomass storage and timber extraction in New Britain, Papua New Guinea 69

13. Systems diagram of willow plantation production and fuelwood harvest under 4 year rotation schedules in southern Sweden 74

14. Systems diagram of eucalyptus and melaleuca plantation production and fuelwood harvest under 5 year rotation schedules in south Florida 77

15. Systems diagram of siris plantation production and possible fuelwood harvest under 11 year rotation schedules in Puerto Rico 82

16. Systems diagram of above ground production and biomass storage in four natural tropical forest ecosystems in the Luquillo Experimental Forest, Puerto Rico 88

17. Systems diagrams of possible reforestation of degraded agricultural lands to secondary forests in Puerto Rico: (a) assisted reforestation using plantations as foster ecosystems; (b) natural reforestation through successional organization of native and introduced species 96

18. Systems diagrams of water cycles in four forested watersheds of the Luquillo Experimental Forest, Puerto Rico: (a) overview diagram of energy flows and transformations of water; (b) solar empower of incident rainfall, forest evapotranspiration and surface water runoff 100

19. Systems diagram of wood chip production and use as an alternative biomass fuel for district heating in Sweden 106

20. Systems diagram of wood powder production and use as an alternative biomass fuel for district heating in Sweden 112

21. Systems diagram of chemical production of one ton of wood pulp 113

22. Systems diagram of mechanical production of one ton of wood pulp 115

23. Systems diagram of production of one ton of paper 118

24. Systems diagram of annual environmental production and economic services supporting multiple-uses in Luquillo Experimental Forest, Puerto Rico 122

25. Systems diagrams of electricity production at four generator substations in Gainesville, Florida 132

26. Aggregate systems diagrams for electricity production (1 MWh) using four non-renewable fuel sources in Thailand: (a) natural gas; (b) coal; (c) oil; (d) lignite 143

27. Systems diagrams of theoretical wood-fired electricity production in Sweden: (a) wood chips; (b) wood powder 145

28. Systems diagrams of wood-fired electricity production: (a) proposed 25 MW capacity plant in Thailand; (b) 53 MW plant in Jari, Brazil 152

29. Environmental and economic components of solar transformities for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass, rank ordered by cycle time 160

30. Emergy yield ratio as a function of economic feedback for evaluated agro-forest ecosystems: (a) silvicultural forest production; and (b) harvested biomass 162

31. Solar transformity as a function of emergy investment ratio for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass 163

32. Emergy yield ratio as a function of cycle time for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass 165

33. Emergy investment ratio as a function of cycle time for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass 167

34. Environmental and economic components of solar transformities for evaluated systems of electricity generation: (a) primary fuel source; and (b) electricity 170

35. Emergy yield ratio as a function of economic feedback for evaluated systems of electricity generation: (a) primary fuel source; and (b) electricity 172

36. Solar transformity as a function of emergy investment ratio for evaluated systems of electricity generation.: (a) primary fuel source; and (b) electricity 173

37. Effect of of increasing electric generating capacity on (a) solar transformity; (b) emergy yield ratio; and (c) emergy investment ratio for electricity from natural gas and coal-fired plants 175

38. Systems diagrams of biomass production, storage, fuelwood development and heat generation from agroforest systems under three different management schedules in southern Sweden: (a) natural, old growth spruce; (b) managed spruce/pine; (c) plantation willow 178

39. Comparisons of measurements for three agroforest systems under different rotation schedules for the development of fuelwood for possible heating and electricity generation: (a) solar transformity; (b) emergy yield ratio; and (c) emergy investment ratio 179

40. Comparisons of measurements for three agroforest systems under different rotation schedules for the development of fuelwood for possible heating and electricity generation: (a) emergy per ton fuelwood; (b) annual available energy yield; (c) equivalent land area requirements . . . 180

41. Systems diagram and equations for simulation model determining biomass production and emergy yield ratio as a function of cycle time for agro-forest systems 183

42. Computer simulation of forest development as a function of cycle time: (a) gross and net production; and (b) above ground biomass accumulation 185

43. Computer simulation of emergy yield ratio as a function of cycle time: (a) net above ground production; and (b) harvested biomass 187

44. Emergy yield ratio as a function of emergy investment ratio for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass 188

45. Systems diagram and equations for minimodel of general production relating indices of energy yield and investment 190

46. Computer derivation of the relationship between (a) emergy yield and investment ratios; and (b) solar transformity and investment ratio for minimodel of general production 191

47. Solar transformity as a function of biomass production and storage for evaluated agro-forest ecosystems: (a) empower of above ground production; and (b) emergy stored in above ground biomass 196

48. Solar transformity of surface water runoff as a function of empower for elevational forest watersheds of Luquillo Experimental Forest, Puerto Rico: (a) gravitational potential energy; and (b) chemical potential energy 199

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

EMERGY EVALUATIONS OF AND LIMITS TO FOREST PRODUCTION

By

Steven James Doherty

December 1995

Chairman: Howard T. Odum
Major Department: Environmental Engineering Sciences

Temperate and tropical forest systems in Sweden, Puerto Rico and other areas, ranging in age from 5 and 300 years, were evaluated with energy systems methods to investigate net yields, economic requirements, and limits of biomass production from solar energy. Inputs and products were measured on a common basis in units of solar emergy (solar emjoules--the solar energy required directly and indirectly to produce a product or service). Forest growth and harvested biomass, were compared along with water supply, reforestation, pulp, paper, and recreational use.

Net emergy yields increased with length of growth cycle, ranging from 1.5 for plantations to more than 12 for unmanaged forests with economic investments as much as ten times greater for managed systems. Preparing biomass for conversion to electricity required greater emergy inputs than was required for processing fossil fuels.

Emergy yield ratios for natural gas and coal-fired were between 3 and 6 and less than 2 for wood-fired electricity.

Solar transformity, a measure of emergy used per unit energy produced, for above ground biomass production was less than 10,000 sej/J (i.e., solar emjoules per joule) and between 100,000-200,000 sej/J for electricity. The lowest value in each category may approach the most efficient conversions thermodynamically possible consistent with operation at maximum production. In Puerto Rico, reforestation using plantations (34 years) and exotic invasions (50 years) minimized economic requirements and increased net yields.

Emergy yield is inherently dependent upon growth time for biomass systems. Sustainable long-run forests which rely on flow limited, renewable emergy often exhibited greater net production than managed short rotation forests, yet net biomass production is often smaller because more is reinvested to design and maintain diverse structure and autogenic pathways. Although technology may increase energy conversion efficiencies, additional investments reduce net yields below currently available primary sources.

Because of energy conversion and temporal limits to biomass production, agroforest systems cannot currently compete with fossil-carbon fuels, until nonrenewable sources become limiting, lowering net yields for all existing fuels. Human carrying capacity would be less than half its current size and a general slowing of global economies would be necessary if only renewable fuel sources were available.

INTRODUCTION

To replace the nonrenewable sources of fuel and electricity as their availability declines, research continues for renewable alternatives. One of the main possibilities is solar-based, organic biomass from agriculture and forestry. Major theoretical and practical questions include: 1) what are the best possible net yields from biomass; 2) are there biophysical limits to biomass production; and 3) how is time related to net resource yield? In this dissertation, energy systems methods are used to evaluate production and multiple-use of a wide range of agroforest systems under different management schedules from temperate and tropical latitudes. Net emergy measures are used to compare biomass fuels with current alternatives in the generation of heat and electricity. Energy-based measures are compared with market values for forest products. An effort is made to determine the thermodynamic maximum production of biomass. By considering full cycles of growth, harvest and regrowth, net yields are related to the rotation period. Computer simulation is used to relate inputs, cycle time, and yield. The discussion considers the implications of biomass limits for world reforestation, human carrying capacity, and global environmental-energy policy.

Forest systems worldwide are increasingly being reorganized by human interactions. Old growth forests are cleared and replaced with managed ones; silvicultural practices are reducing the turnover time of forest biomass; forests are often burned or are replaced by some other land-use. Following a century of forest exploitation, now global in scale, new and old systems of utilization are needed that are both productive and sustainable. Further, as the availability of fossil fuels decreases, the controversy increases over what is the maximum sustainable conversion of biomass and fuels from renewable solar energy. Recognition and quantification of the full range of values forests provide, including those outside the market economy, are needed in order to determine best uses of forest ecosystems worldwide. Issues such as these require new and comprehensive assessments if scientists, land managers and ultimately policy makers are to make sound decisions regarding our forest resources and their roles in future questions of energy supply and global processes.

Issues and Research Objectives

Sustainable, long-run natural forest systems which rely on renewable environmental energies, often exhibit greater gross production than managed plantations, yet generally have smaller net yields. This is because more of their production is re-invested to design and maintain diverse structure and cooperative pathways (Figure 1a). In agriculture and forest plantations, feedbacks in the form of fossil fuels, irrigation, pest management, planting and thinning direct more of the gross production into extractable biomass producing greater yields per unit time (Figure 1b). Agro-ecosystems which are reliant on purchased subsidies often increase yields, but because of large investment requirements, may deliver little "net" contribution, possibly with required inputs being diverted from more competitive or efficient activities within the regional economy.

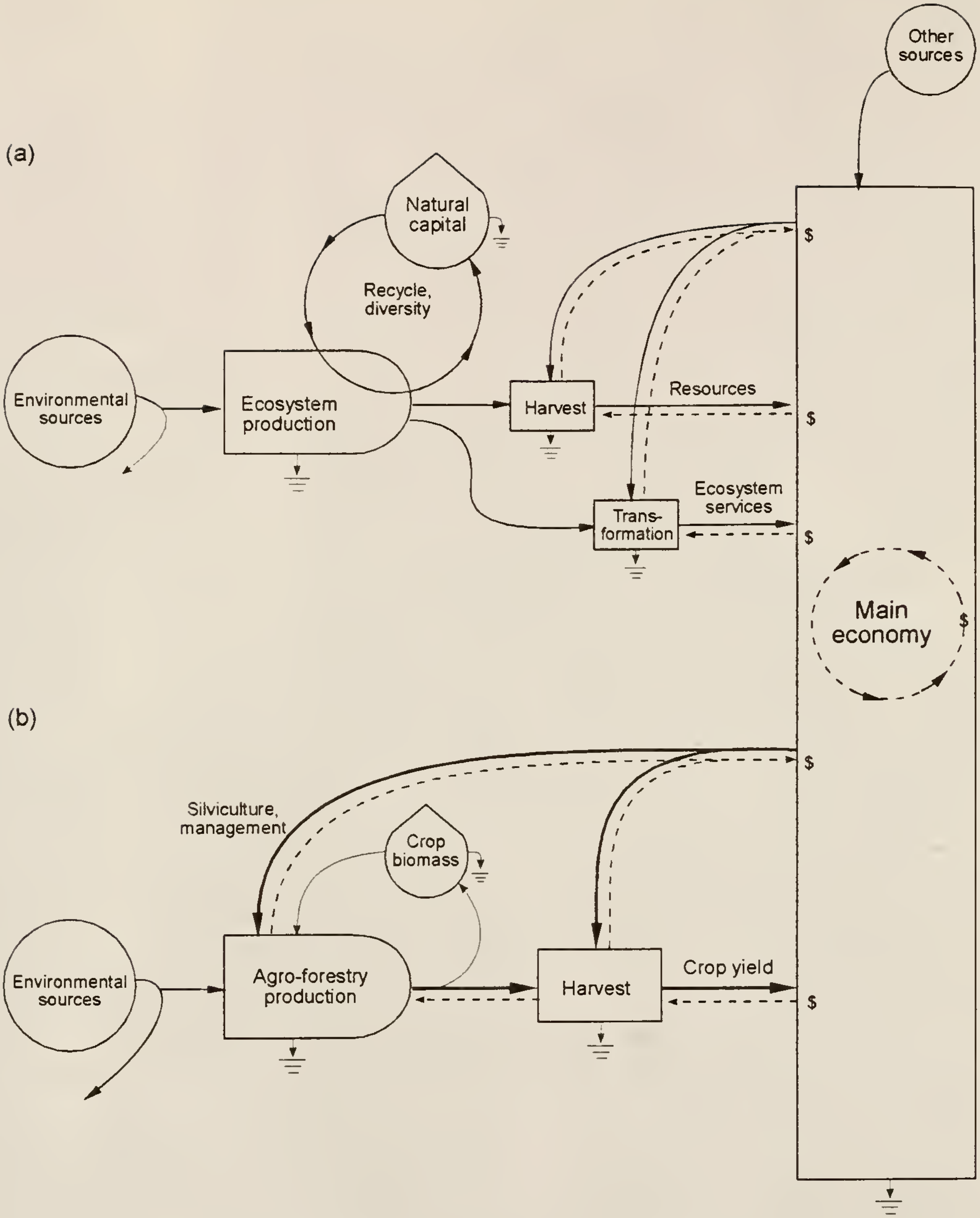


Figure 1. Systems diagram relating principles of self-organization, maximum power, thermodynamic efficiency and net yield for two paradigms of resource use: (a) natural, unmanaged ecosystems; (b) managed agro-forest systems. Thickness of pathway lines and size of symbols were drawn to illustrate relative differences in flow rates and quantities stored.

Silviculturally managed forests shorten the rotation time between harvestable yields of forest biomass. Managed forest stands are clear-cut on rotations ranging from 25 years for pine in the southeastern U.S. to 80 years or more for northern mixed coniferous forests in Sweden. Plantations harvest fuelwood as often as every 4 years. Cleared land is often scarified; seedlings are planted; the stands are thinned; access roads and drainage ditches are built and maintained. Thinning operations act to reduce competition for resources, increasing available sunlight, precipitation and soil nutrients for the remaining trees, generally increasing productivity. Fuelwood and pulpwood yields may be delivered from thinning operations, and the remaining trees have greater stemwood volume and wood density making the trees of the final harvest more commercially valuable. All of these attributes require economic inputs, reducing the net yields of delivered products.

All resources and ecosystem processes require a minimum amount of energy for production and maintenance. Ecosystems, through processes of self-design, may maximize gross production based on flow limited, renewable resources. Natural systems may be more efficient systems than managed agro-ecosystems, although their turnover times, and thus their rates of delivery are slower. This postulate and limits to the conversion of biomass from solar energy suggest a thermodynamic minimum transformation of total resources supporting production.

Thus, there is a trade off between management resources and rate of delivery of forest products. The tradeoff lies in the increased investments required for shortened rotations and increased yields. Traditional economic accounts of forestry systems often support increased management initiatives; biophysical accounts of forest operations often argue for less investment, slower returns but greater net yields.

Often, only forest products with current market value are recognized, and non-market services such as carbon storage, watershed protection and wildlife habitat are not considered in conventional benefit/cost studies. If these other "co-product" or non-target services are considered, the net benefits derived from forests may be larger than the price of forest products. Growing forests for wood ignores the other contributions that a well-organized ecosystem proffers.

Finally, renewable fuels are increasingly being reconsidered as alternatives to fossil and nuclear fuels as supplies of these fuels diminish and concern for the environment increases. Biomass fuels are being promoted as competitive and viable alternatives since carbon emissions are abetted by forest production. However, these assessments do not consider indirect carbon emissions from activities necessary to develop the resource nor do they consider the important role of time in developing high net yields. Primary fuels with high net yields may emit lower carbon dioxide levels per unit output. These issues suggest that forests offer multiple services, and that single-use management may not properly assess whole system benefits.

Energy Systems Language

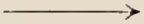
Ecosystem concepts, system configurations, and computer models are represented in this dissertation with energy circuit language (Odum 1971, 1983, 1995a). A symbolic language for modelling systems of all kinds, symbols are used to represent system components including storages, flows and sources. The symbols have specific mathematical and energetic relationships when drawn in ordered fashion into energy systems diagrams. These symbols are defined in Figure 2; diagramming conventions are given in the Methods section of this study. Systems diagrams are like graphical inventories and impact statements. Energy circuit language helps recognize and represent networks, organization and order within systems.

Concepts and Definitions

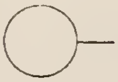
General Systems Principles

Systems theory arose from the observation that models describing and predicting diverse "systems" often have certain common or similar principles which influence the design and outcome of the models. In Figure 3, principles of self-organization, hierarchical ordering and energy transformation are illustrated as thermodynamic principles common to all systems. Table 1 lists definitions of terms and central concepts used in this study. Below are further discussions of general principles.

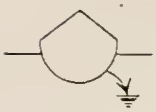
Using concepts from ecology, an energy hierarchy is identified in Figure 3a (Odum 1987) in which many small components with short life spans (rapid turnover) and small territories are required to support few large individuals with greater life longevity and larger territories. Common to all levels or systems shown here is an energy source shown at the left and converging through transformations at the right of each diagram. As the solar energy is transformed from one type of energy to another,



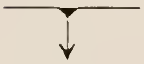
Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.



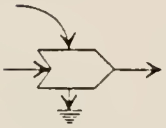
Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.



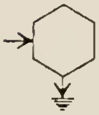
Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.



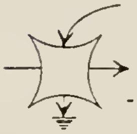
Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.



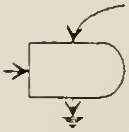
Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.



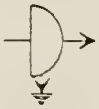
Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.



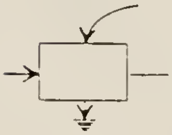
Switching action. A symbol that indicates one or more switching actions.



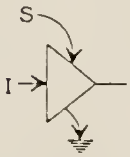
Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.



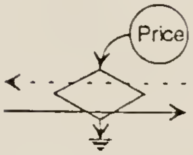
Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.



Box. Miscellaneous symbol to use for whatever unit or function is labeled.



Constant-gain amplifier. A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy source S is sufficient.



Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 2. Symbols and definitions of energy language diagramming used to represent systems (Odum 1983).

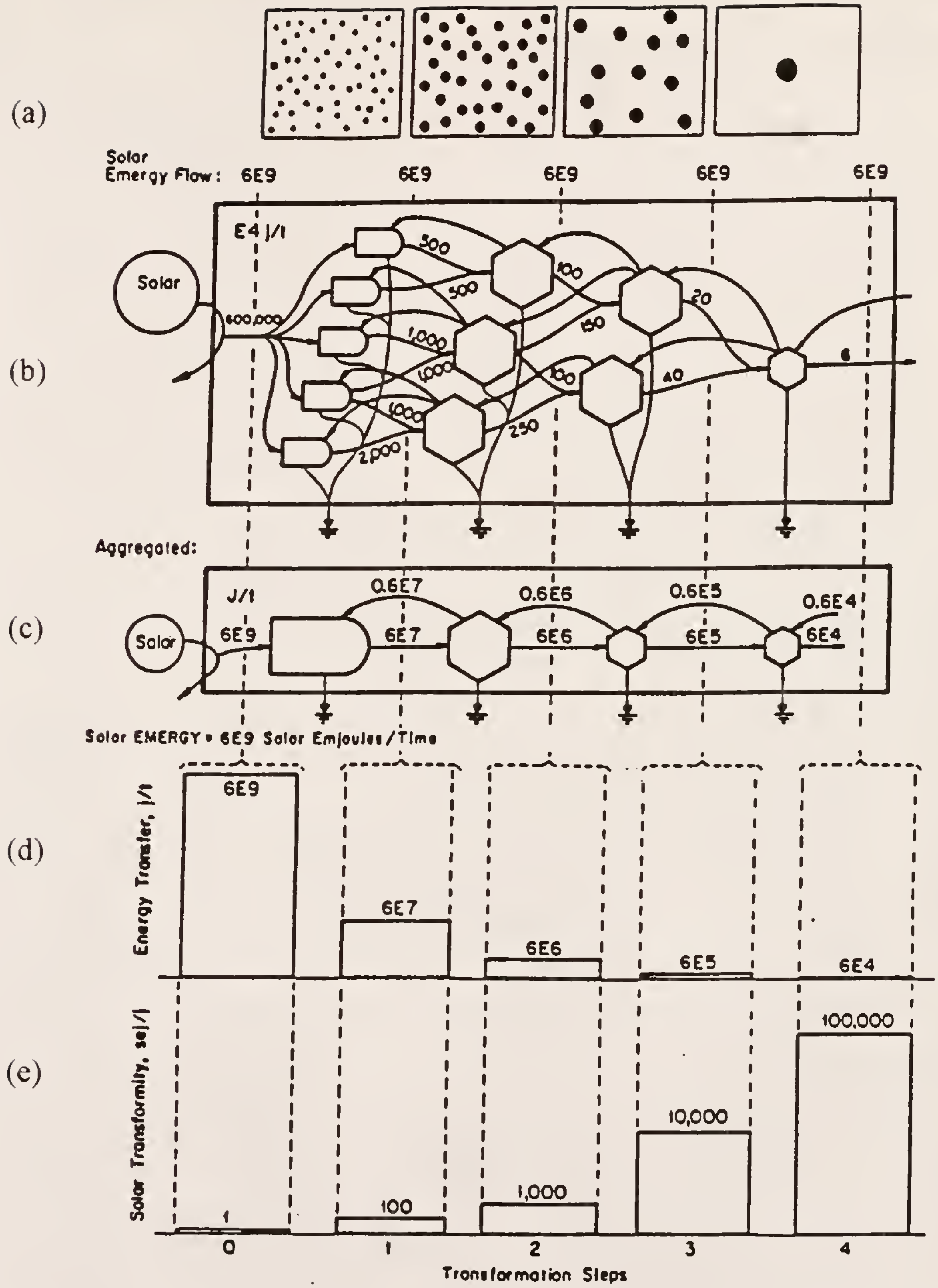


Figure 3. Energy transformations and hierarchical ordering of ecosystems illustrating the concept of solar emergy: (a) spatial pattern; (b) system network; (c)network aggregation by hierarchical levels; (d) sequential energy flows; and (e) solar transformities (Odum 1988).

Table 1. Definitions of central concepts and units used throughout this study.

1st law of thermodynamics: Also termed the law of conservation of energy, this principle states that energy is neither created nor destroyed, thus energy entering a system must be accounted for as either stored or outflowing.

2nd law of thermodynamics: This principle states that all energy transformation processes degrade energy -- that available energy loses its ability to do useful work. Energy lost to a system is identified as degraded heat with an overall entropy increase.

Energy: A property of all things which can be turned into heat, energy is measured in heat units [British thermal units (BTU), kilocalories (kcal), or joules (J)].

Available energy: Potential energy capable of doing work and being degraded in the process. This is also termed exergy.

Used energy: Energy whose availability has been used up in a transformation process according to the second law and no longer able to accomplish useful work.

Renewable energy: Energy flows, such as sunlight, rainfall and wind, generally recurring and which ultimately drive the bio-chemical processes of the earth and contribute to geologic processes. Renewable sources are ultimately limited by their flow rates -- systems cannot draw from these sources any faster than they are delivered.

Nonrenewable energy: Energy and material storages that are used up at rates faster than replacement. Examples include fossil fuels, mineral ores and soils.

Gross photosynthetic production: Energy transformed through photosynthesis, often measured as total carbon sequestered in plant biomass or as oxygen produced.

Net production: Available energy flow or storage remaining after one or more flows are subtracted.

Efficiency: The ratio of useful energy output to total energy input to a production system.

Net storage turnover time: The time required for the replacement of a quantity, obtained by dividing the quantity by the difference between the inflow and outflow rates.

Cycle time: The period of time lapsed between the beginning and end of an oscillation. It is used here to quantify forest rotations of growth, harvest and regrowth.

Market value: The price, assigned a commodity or activity addressing the human services rendered in recovery, production and delivery (i.e., market supply) and subject to demands of the consumer. It is an assessment of opportunities forgone from using resources in the present and thus lost to the future.

Gross economic product: The total market monetary value of all final goods and services produced in an economy in one year.

Table 1--continued.

Emergy: Available energy of one kind previously used up, directly and indirectly, to make a product or service.

Solar emergy: The solar energy used up directly and indirectly through transformations to make a product or service.

Solar emjoule: The unit of measure of solar emergy, abbreviated **sej**.

Empower: The flow of emergy per unit time.

Solar transformity: The ratio of solar emergy used up in a transformation process divided by the available energy yielded, measured **sej/J** (Figure 4a).

Energy transformation hierarchy: Systems self-organize such that energy flows are hierarchical with many joules of kind of energy required in trasnformations to produce the next kind. Transformities measure position within energy hierarchies.

Maximum empower principle: Systems that tend to prevail are those that take the most effective advantage of available emergy. Systems, economic or ecological, accomplish this by: reinforcing productive processes, drawing more resources, and overcoming more limitations through effective system self-organization.

Feedbacks: Consumer pathways that reinforce productive flows and help develop optimum efficiencies.

Emdollar (em$): The portion of gross economic product attributed to an emergy-use. The em$ is obtained by dividing an emergy flow or storage by the sej/money index for a region/nation.

Emergy/money ratio: A measure of emergy-use supporting economic activity, generally calculated by dividing the gross economic product of a region into the area's annual emergy use, measured in units of **sej/$**.

Net emergy yield: Emergy derived from a productive process minus emergy fedback from economic sources (Figure 4b).

Emergy yield ratio: (YR) The emergy output from a productive process divided by the emergy fed back from economic sources (Figure 4b).

Emergy investment ratio: (IR) The emergy from economic sources divided by environmental emergy sources (Figure 4b)

Emergy exchange ratio: The ratio of emergy received to emergy delivered in a trade or sales transaction (Figure 4c).

---

losses occur according to the second law (Figure 3b). Therefore very little available energy remains after several transformations of the original energy. Because each of these steps is required, the total influx of independent energies (in this example there is only one--sunlight) is required to support each transformation step (Figure 3c). It takes increasingly more solar energy to support a given unit of energy going from left to right along the energy hierarchy (Figure 3d).

The solar transformity estimates the amount of available energy of one type (i.e., solar) required through transformations to produce the available energy of another type (Odum 1983, 1988; Scienceman 1987). It is a measure of position and influence within a system. The work that potential energy can do is then dependent upon its position in the hierarchical web of energy transformations. A list of the solar transformities and indices of solar emergy per unit mass and solar emergy per gross economic product, used to convert environmental flows, purchased fuels, commodities, and human services to solar emergy in this study, is given in Table 2. The method of calculating solar transformities in this study is given in Figure 4a. Since human services are calculated separately as inputs to production, to reduce the error of double counting, transformities for primary fuels and electricity used as system inputs in this study (items 9-13, Table 2) were considered lower conversion limits without economic services.

Solar emergy is defined as the product of the available energy and its solar transformity (Odum 1983, 1988). It may be a measure of real contributions commensurate to its requirements. Solar emergy is the common unit of measure used in this study to address questions of resource-use and net yield in forest systems.

Table 2. Solar transformities (*sej*/J), emergy per unit mass (*sej*/g) and emergy/money ratios (*sej*/$) used in this study to convert resource measures into units of solar emergy. Calculations for additional conversion values are given as footnotes accompanying emergy evaluation tables. Solar transformities derived from evaluations in this study are denoted ST_i.

Note	Item	Solar emergy per unit	
1	Solar energy	1	sej/J
2.	Wind, kinetic energy	1500	sej/J
3.	Rain, gravitational potential energy	10,500	sej/J
4.	Rain, chemical potential energy	18,200	sej/J
5.	Physical stream energy	27,800	sej/J
6.	Chemical stream energy	48,450	sej/J
7.	Soil organic matter	74,000	sej/J
8.	Lignite	37,000	sej/J
9.	Coal	29,000	sej/J
10.	Natural gas	34,800	sej/J
11.	Crude oil	40,200	sej/J
12.	Refined petroleum	47,900	sej/J
13.	Electricity	1.25E+5	sej/J
14.	Irrigation water	2.55E+5	sej/J
15.	Concrete	1.5E+06	sej/g
16.	Machinery, steel prod.	6.7E+09	sej/g
17.	Fertilizer, general	4.8E+09	sej/g
18.	Potassium	2.0E+09	sej/g
19.	Nitrogen	4.2E+09	sej/g
20.	Phosphorus	2.0E+10	sej/g
Human services:			
21.	Sweden	1.53E+12	sej/$
22.	U.S.	1.60E+12	sej/$
23.	Puerto Rico	1.64E+12	sej/$
24.	Thailand	3.69E+12	sej/$
25.	Brazil	6.09E+12	sej/$
26.	Papua New Guinea	4.80E+13	sej/$

Notes.

1. Solar energy by definition = 1 sej/J (Odum 1988, 1995a)

2. Wind used at surface of the earth estimated as 10% of total flux of wind energy): (2.0E+12 kW) (1 J/sec/watt) (1000 W/kW) (3.154E+7 sec/yr) (10 %) = 6.31E+21 J/yr; ST = (9.44E+24 sej/yr, global emergy flow (Odum and Odum 1983, Odum 1995a) / (6.31E+21 J/yr) = 1496 sej/J

Table 2--continued.

3. Physical energy of rainfall on elevated land: world's rain over land = 105,000 km^3/yr; average elevation of land = 875 m; (1.05E+5 km^3) (1E+12 kg/km^3) (9.8 m/sec^2) (875 m) = 9.0E+20 J/yr; ST = (9.44E+24 sej/yr, global emergy flow) / (9.0E+20 J/yr) = 10488 sej/J

4. Chemical potential energy of rain: world's rain over land = (1.05E+14 m^3/yr) (1E+15 g/km^3) (4.95 J/g Gibbs free energy) = 5.187E+20 J/yr; ST = (9.44E+24 sej/yr, global emergy flow) / (5.187E+20 J/yr) = 18199 sej/J

5. Physical energy in stream flow: (3.96E+4 km^3/yr global runoff) (1E+12 kg/km^3) (9.8 m/sec^2) (875 m, average world elevation) = 3.395E+20 J/yr; ST = (9.44E+24 sej/yr, global emergy flow) / (3.395E+20 J/yr) = 27806 sej/J

6. Chemical potential energy in streams: (3.96E+4 km^3/yr, global runoff) (1E+15 g/km^3) (4.92 J/g, Gibbs free energy at 150 ppm typical dissolved solids) = 1.948E+20 J/yr; ST = (9.44E+24 sej/yr, global emergy flow) / (1.948E+20 J/yr) = 48460 sej/J

7. Odum et al. (1983); updated in Odum (1995a)

8. Odum et al. (1987)

9. Sedimentary coal, in situ; ST = 29,000 sej/J; 39800 sej/J for processed coal (Odum 1995a)

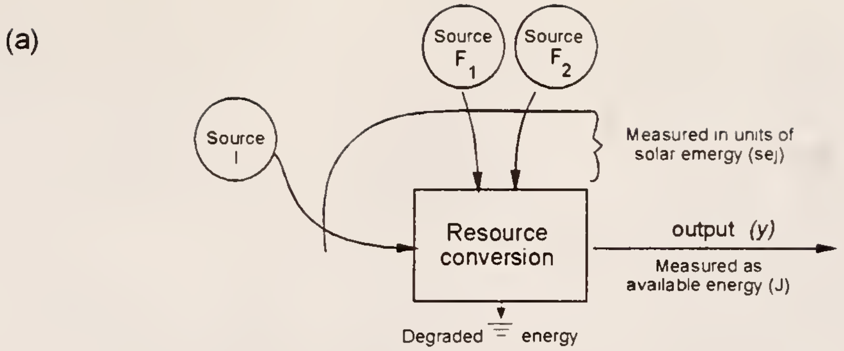
10. Natural gas = 20% more efficient in boilers than coal (Cook 1976); est. ST (without services) = (1.2) (29000 sej/J; item 7) = 34800 sej/J; 48000 sej/J for processed nat. gas (Odum 1995a)

11. Crude oil: Refinement and transport of refined fuels uses 19% crude petroleum (Cook 1976); est. ST (without services) = (47850 sej/J; item 11 below) / (1.19) = 40200 sej/J, 53,000 sej/J for processed, delivered crude oil (Odum 1995a)

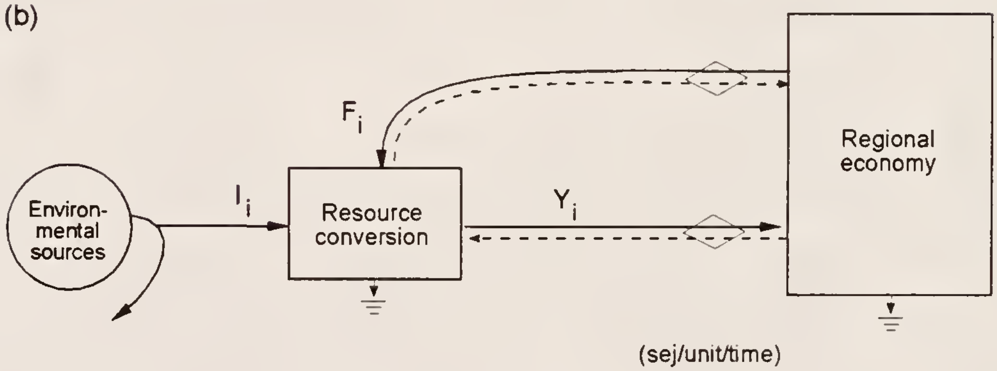
12. Refined fuel oils: 1.65 coal-J/oil-J (Slesser 1978); est. ST (without services) = (1.65) (29000 sej/J) = 47850 sej/J; 66000 sej/J for processed, delivered oil (Odum 1995a)

13. Electricity: 2.6 fuel-J/electricity-J (Swedish Power Assoc. 1981); est. ST (without services) = (2.6) (47850 sej/J) = 124,500 sej/J; Odum (1995a) uses 2.0E+5 sej/J.

14. Odum et al. (1987)
15. Brown and McClanahan (1992)
16. Odum and Odum (1983)
17. Fertilizer estimated from weighted average of items 18, 19, 20 below, assuming typical forestry N:P:K ratio of 30:3:10
18. Odum and Odum (1983); updated in Odum (1995a)
19. Odum and Odum (1983); updated in Odum (1995a)
20. Odum and Odum (1983); updated in Odum (1995a)
21. Doherty et al. (1993)
22. Odum (1995a) for 1990 (U.S. sej/$ ratios for other years are identified as footnotes to tables)
23. Doherty et al. (1994)
24. Brown and McClanahan (1992)
25. Comar (1993)
26. Doherty and Brown (1992)



$$\text{Solar transformity for output} = \frac{\text{emergy of inputs (sej)}}{\text{energy of output (J)}} = \frac{(I + F_1 + F_2)}{y}$$



YR_i Emergy yield ratio . . . . Y_i / F_i

IR_i Emergy investment ratio . . . . F_i / I_i

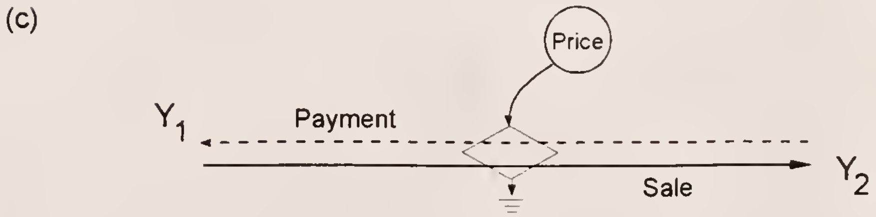


Figure 4. Calculation of measurements made for resource-conversion systems: (a) solar transformity; (b) emergy ratios of yield and investments; (c) emergy exchange ratio (Y2/Y1) of economic transaction (Y1 = monetary payment multiplied by emergy/money ratio for region and Y2 = emergy flow of sales).

As available energy dissipates and is used up through transformations (Figure 3), the solar emergy remains unchanged, because at each step all previous energy transformations are required, going back to the original source at the left, solar power.

A general hypothesis emerges from an understanding of thermodynamic laws, energy transformations and hierarchical ordering: systems organize over time to develop structures and cooperative pathways that stimulate productive processes which capture and use effectively the available energy. Components and processes at the top of the hierarchy, requiring a lot of source energy, contribute to lower level processes through feed back mechanisms which amplify lower level actions. These include autocatalytic processes to insure and increase the influx of energy from available sources and optimize efficiency that is compatible with maximum use.

This principle of maximum empower (Odum 1988, 1995a) states that the system design (i.e., production system or development alternative) that will prevail in competition with others is the one that develops designs with reinforcement actions, that yield the most useful work using inflowing emergy sources. Energy dissipation without "useful" contributions does not reinforce and thus cannot compete with systems that use inflowing emergy in self-reinforcing ways.

The thermodynamic minimum transformity is defined here as the lowest possible amount of emergy necessary to produce a quantity or sustain a process. It is argued here that reforestation and forest rotation systems that require more than the thermodynamic minimum are inferior as measured by the deviation from the best value of net emergy per cycle time.

Another theorem investigated here is that the area receiving the more solar emergy due to the market transaction has its economy stimulated more. Previous studies have indicated that raw products such as minerals, rural products from agriculture, fisheries, and forestry generally tend to have high net emergy benefits to purchaser when sold at market price (Odum 1984, Odum and Arding 1991, Doherty and Brown 1992). This is a result of money being paid for human services and not for the extensive work of nature that went into these products.

Indices of Resource Use, Efficiencies, and Exchange

By keeping track of the origins of resources in production systems, whether from they are economic sources or from environmental sources, renewable or non-renewable, indices of yield, investment and exchange can be calculated to synthesize analyses and make comparisons between systems. In the indices that follow, resources required to produce a yield (Y_i) are identified as either environmental in origin (I_i) or economic (F_i).

The emergy yield ratio is the emergy of an output (Y_i) divided by the emergy of those inputs to the process that are purchased from the economy (F_i) (Figure 4b). This ratio indicates whether the process can compete in supplying a primary energy source for an economy. Typical, competitive fuel sources on world markets have been between 3 and 15, but are usually about 4 or 6, though these favorable ratios are declining as fossil reserves decline and extraction and processing costs increase (Odum 1995a). Since fuels can be substituted, processes with yield ratios less than available fuels may not be currently economic as primary sources.

The emergy investment ratio is the ratio of emergy derived from the economy (F_1) to the emergy delivered "free" from environmental sources (I_1) (Figure 4b). This ratio indicates if the process is competitive as a utilizer of the economy's investments in comparison with alternatives. To be competitive, the process should have a similar ratio to its competitors. If it receives less from the economy, the ratio is lower and its prices are lower so that it will tend to compete in the market place. Prices are lower when a production process is receiving a higher percentage of its useful work from environmental inputs than its competitors. The investment ratio can also be considered an environmental loading ratio, a measure of potential impact or "loading" a particular development activity can have on its environment.

The emergy exchange ratio is the ratio of solar emergy received to solar emergy delivered in a sales transaction. It is calculated as the solar emergy of the product sold divided by the solar emergy that could be purchased with the earned revenue (Figure 4c). Dollar revenues are converted to solar emergy using the emergy/money ratio (defined next) for the purchasing region.

An index of annual emergy-use and gross economic product of a region (emergy-use/GP) is considered an estimate of the solar emergy supporting each unit of currency circulating in the economy for a particular year. In general, rural countries tend to have higher emergy/money ratios because more of their economy involves direct environmental resource inputs that are not paid for (Odum and Odum 1983, Odum and Arding 1991, Doherty and Brown 1992).

The term emdollar (abbreviated em$) refers to the total amount of dollar flow generated in an entire economy supported by a given amount of solar emergy input from a production sector. It is calculated by dividing the solar emergy of a product or process by the emergy/dollar ratio for the economy to which it contributes. This is a method of putting a monetary value on services and storages not traditionally accounted for in economics such as transpired rainfall, photosynthetic production, forest biomass, and information. This is not a market value, but instead a value for public policy inferences and directives.

Resource development projects can be evaluated and compared among alternatives and net contributions of sectors typical for a region so that decisions can be made in advance of implementation (Figure 5). In this study, proposed forest-uses are compared with alternatives and with current sectors using the resource indices defined above. Best uses are considered those that maximize emergy flow for the region and draw the highest net emergy.

Usually questions of development policy and resource-use involve environmental impacts that must be weighed against economic gains. Often impacts and benefits are quantified in different units resulting in a paralysis of the decision-making process because there is not a common means of evaluating the tradeoffs between environment and development. The systems analysis procedure is designed to evaluate the flows of energy, information, materials and money in common units that enable one to compare environmental and economic aspects of systems. Measurements in this study were organized to evaluate thermodynamic properties common to all systems; each component of a self-organized system is coupled to lower and higher levels and all components contribute to system performance commensurate to their position, transformity and emergy.

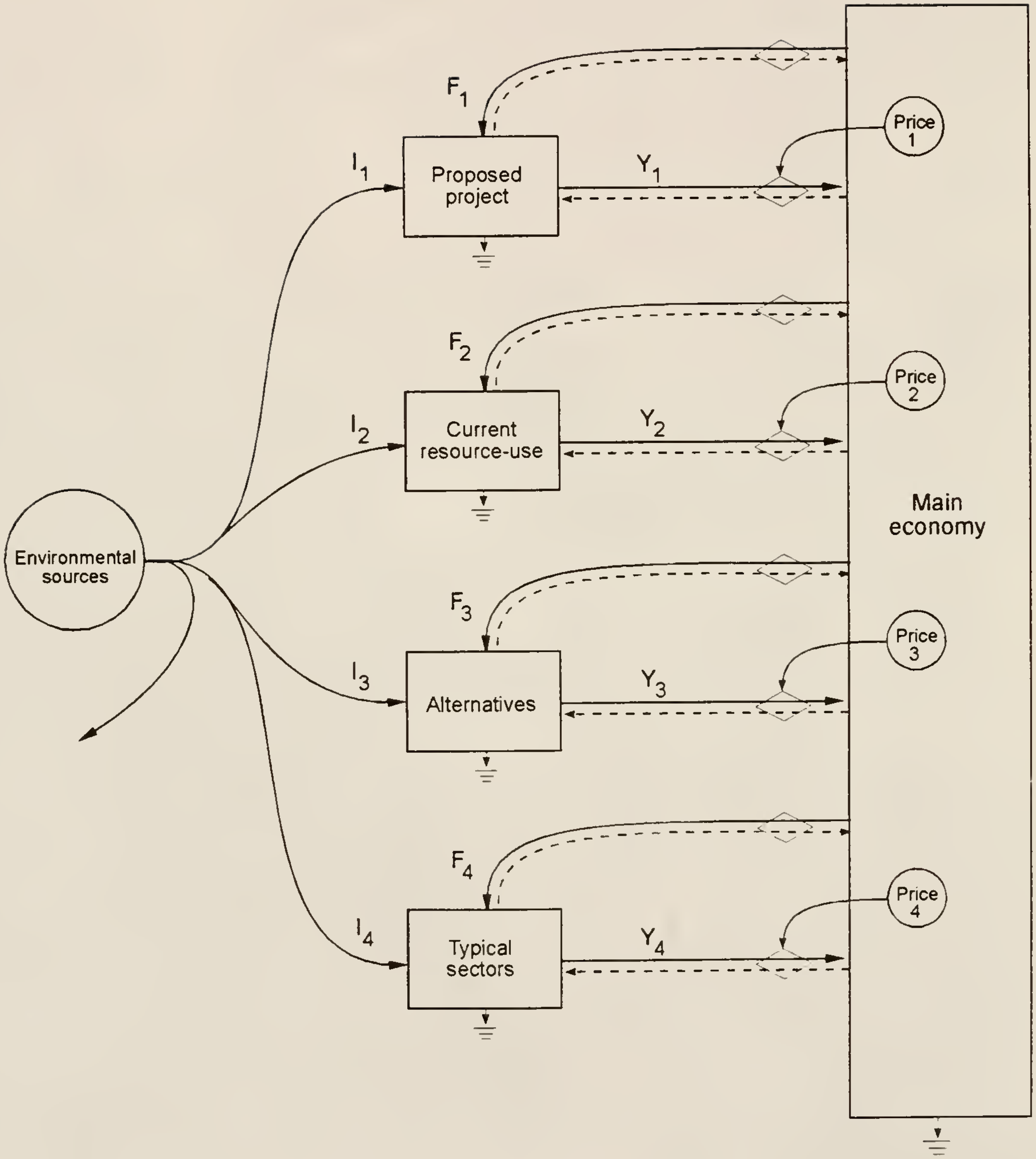


Figure 5. Overview diagram for comparing regional benefits of a proposed resource-use system with the current one it would replace or with other sectors typical of the region. Environmental sources (I) are matched with economic sources (F) at a scale of the regional emergy investment ratio.

Review of Literature on Energy Analyses and Biomass Yields

Limits to Biomass Production

Biomass production for fuel-use is limited by a number of factors including conversion efficiencies, amenable and available land area, energy content and concentration of wood, delivery rates, and reductions in net yields due to management investments. Net photosynthetic conversion efficiencies range from less than 1% for trees and most agricultural crops (Slesser 1984) to 3.5% for some C_3 plants and up to 5% for C_4 plants (Keeton and Gould 1993). These values are daily maximums and thus are considered upper conversion limits. A general, mean photosynthetic efficiency for woody biomass systems would likely be below 1%. The sun's energy is flow limited, delivering on average 58E+12 J/ha/yr in the U.S. after albedo and atmospheric absorption are subtracted (Boyles 1984), limiting maximum possible biomass production.

In a discussion of limits to biomass energy supply, Smil (1983) argues that even with very optimistic assessments of biomass conversion of solar radiation, with all productive lands (including agriculture) in the United States cultivated for fuelwood production, biomass energy could still only account for 5-10% of the country's annual energy consumption. Pimentel et al. (1978) present a similar example: the maximum amount of sunlight fixed by all biomass in the U.S. was only about 70% of the total annual use of fossil fuels in 1978; and biomass from agriculture and forestry together was less than 30%. Renewable energy sources are flow-limited (Odum 1983) meaning there is a fixed flow rate limiting ecological systems dependent upon such sources.

These figures are illustrative of the difficulties that could arise if the global economy tried to switch from using non-renewable storages of fossil carbon fuels to renewable sources without down scaling.

Older ecosystems channel more of their productivity into maintenance and diversity, producing very small net annual yields (Figure 6). This is another way of stating concepts outlined in Figure 1. Margalef (1963) proposed that ecosystems develop toward maximum biomass production. In late seral stages of succession, the quotient of production/biomass drops suggesting that more biomass can be maintained for less net production -- a measure of system efficiency. Odum (1970) proposed that ecosystems maximize power not biomass, and only build the amount of biomass that is necessary for maximum gross production.

By considering gross production as a function of biomass instead of the other way around as Margalef (1963) interprets the relationship, a diminishing return on biomass affecting gross production is realized and maintaining biomass levels beyond an optimum level for maximum power is wasteful. There is a point when energy required for maintenance is equal to gross ecosystem production (when net production approaches zero). When the metabolic costs of maintaining structure exceed gross production, mature systems may turnover in order to produce configurations in space and time that maximize empower. This suggests there are optimal rotation periods based on production and stored biomass capacity of ecosystems.

The concept that power is maximized in systems was put forth by Boltzmann (1905) and Lotka (1922) based on earlier ideas from the previous century. Odum and Pinkerton (1955) provided a thermodynamic derivation of the optimum efficiency that

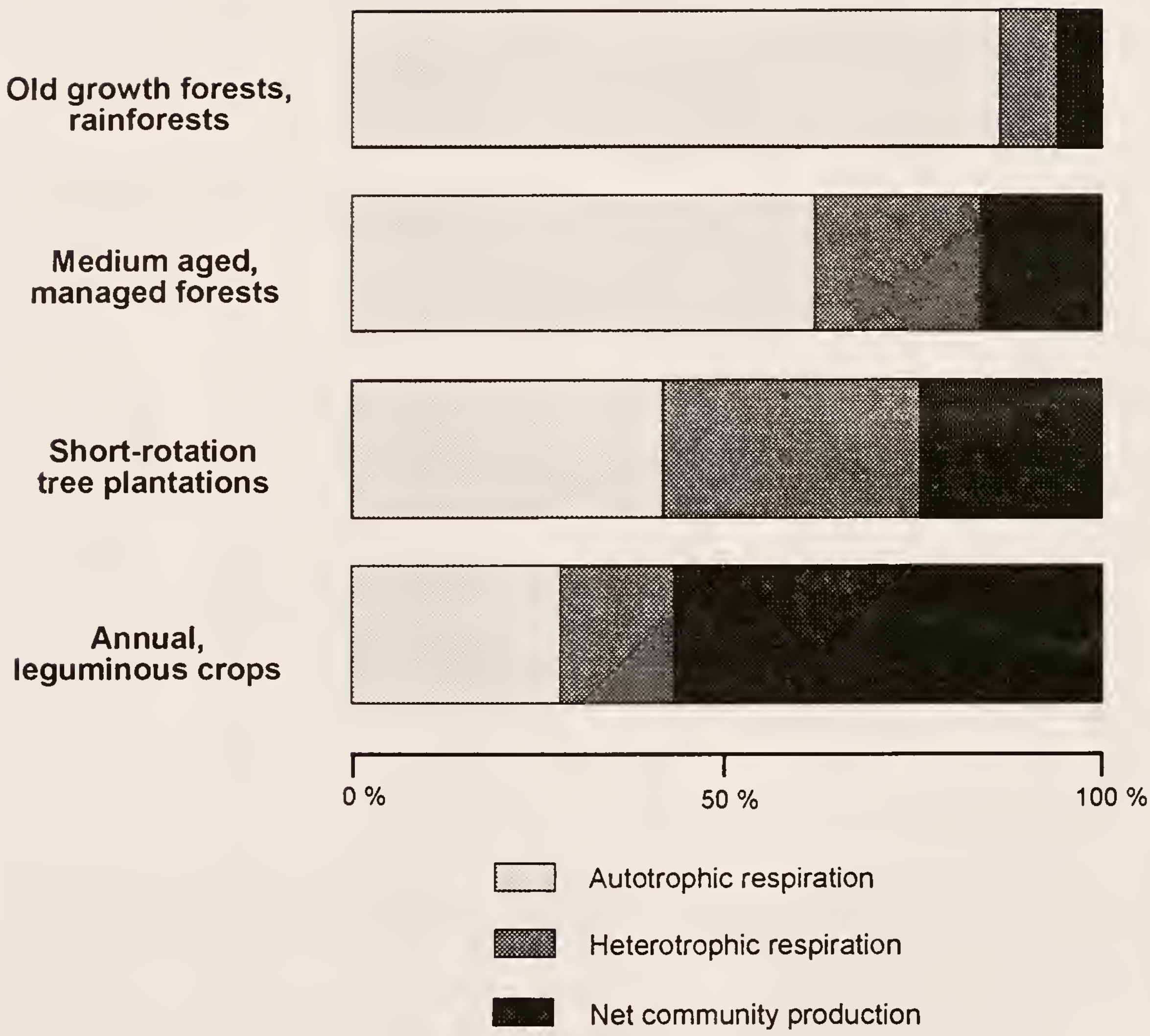


Figure 6. Allocation of gross production in different agro-forest ecosystems. Although gross photosynthesis in natural forests is large, more is used up in community respiration maintaining diverse structure and cooperative pathways. Net productivity is often a small percentage of the gross rate. Yields from annual crops, in contrast, may be as much as two-thirds of gross production. Adapted from Odum (1970) and Smil (1991).

maximizes power in an energy storing process. This was termed "time's speed regulator." This important relationship identified maximum power (i.e., maximum energy flow per unit time) as a function of the loading ratio and showed how time of storage has thermodynamic limits. These early theories are now restated as maximum empower (Odum 1983, 1988) defined in the concepts section of this dissertation.

Spreng (1978, 1988) also introduced the concept of time into energy analysis. He proposed a time-energy-information triad (Figure 7) in which the product is affected by these three parameters. Using forests as an example, net storage of biomass increases with available energy, with useful information and with time of growth. Any point inside the triangle is a combination of all three parameters, and each can be generally substituted for another with all three inputs necessary to produce an output. Perhaps if each parameter was evaluated in emergy units, the sum of all three inputs (100%) along triangular coordinates would equal that of the process output. The author restates the principle that energy conservation measures are time dependent; that efficiency is ultimately related to power output.

Net emergy delivered from resources is a function of resource concentration. Sources of dispersed energy requiring processing to be useful, have low net emergy yields. Processes of concentration and transformation require inputs of time and energy. Renewable, solar-based energy sources are both flow-limited, requiring time to deliver, and dispersed, requiring energy for concentration. Sedlik (1978) proposed a temporal dimension to net energy (termed 'gain function') suggesting that technological advancements can improve net yields while resource depletion acts to lower net yields. This relationship is explored in this dissertation using emergy systems methods.

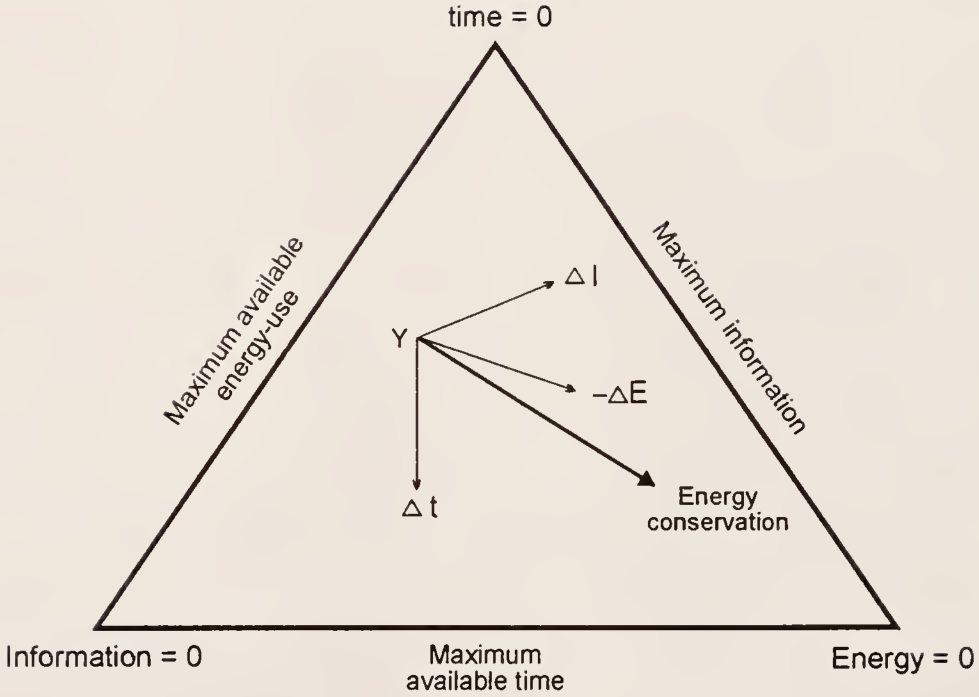


Figure 7. The time-information-energy triangle identifying an output (Y) as a trade off between three parameters (from Spreng 1988). Energy efficiency is identified as a function of power output, which requires information about the system.

A Short History of Energy Analysis

Since the oil crises of the 1970s, the concept of "net energy analysis" has been used to assess the energy requirements of energy systems. Odum (1967, 1971) introduced "net energy" as a new and important concept with his book *Environment, Power and Society*. During this period, new studies and workshops were set up such as the international program coordinated by Malcolm Slesser (IFIAS 1974) to standardize methods and bring together common research (Gilliland 1978). In 1974, the U.S. Congress passed a public law requiring net energy analysis to be a consideration in the evaluation of federal project proposals. There have been many and often divergent schools of net energy analysis, some measuring only direct uses (process analysis) and others measuring both direct and indirect sources or the "embodied energy" supporting production. Spreng (1988) reviews the different approaches.

Two prominent approaches are contrasted by Brown and Herendeen (1995). Embodied energy analysis, using input-output matrix techniques (Hannon 1973, Herendeen and Bullard 1974), assigns resource flows from outside a system to pathways inside according to carrier data such as materials or energy, but more often money. This method assumes that embodied energy is a conservative quantity (Costanza 1980). Odum (1983, 1995a) argues that the assumption of conservation violates the second law since embodied energy disappears when the availability of the transformed products is used up, and that materials, money, energy and embodied energy have different distributions resulting from different principles of circulation. Therefore calculating one from another has no basis.

The method used in this dissertation, net emergy analysis, recognizes that systems have interconnected and interdependent pathways that couple energy inflows from outside (Odum 1995a). Here, co-products are assigned the emergy input to that subsystem or pathway before it "diverges." Pathways are partitioned only if the same product or flow is divided such as electricity going to individual users or sunlight being captured by different canopy layers of a forest. Emergy assigned to co-products can not be added if the co-products converge elsewhere in the system or when pathways feed back to amplify original sources (Odum 1995a; Brown and Herendeen 1995). Because of the differences in theoretical underpinnings and methodology, results from the procedures cannot be directly compared. Examples are given next.

Previous Net Energy Studies of Biomass and Fuels

There is a large and growing body of literature on net energy studies of biomass. Slesser (1987) outlines a general procedure. Smil (1983) and Boyles (1984) review earlier studies. Critics are as numerous as the myriad of different approaches (Leach 1975; Reaven 1986; Jones 1989; Odum 1995a). Most studies of net energy of biomass systems are currently either process analyses of specific systems or some version of input-output analysis for estimating embodied energy using regional or national statistical data (Slesser 1985). The quality of energy inputs is both ignored (Boyles 1984) and addressed using various conversion factors, such as energy intensities (Bullard et al. 1978; Herendeen 1981) and energy coefficients (Pimentel 1980; Fluck et al. 1992) which estimate indirect energies differently determined by the scale of evaluation. Not all inputs are included and not all are treated equally.

Environmental and climatic energy sources are generally not included (Slesser 1985), and labor is variously measured (Fluck 1981) or not at all (Stanhill 1983). The first international workshop on energy analysis (IFIAS 1974) recommended not evaluating labor for industrial applications.

Ratios of net energy include gross energy requirement (GER) per unit production (Leach and Slesser 1976); energy return on investment (EROI; Hall et al. 1986); and net/gross energy ratio (N/G; Herendeen and Brown 1987). Currently there is no convention and indices are variously defined, some including inputs others ignore; some using conversion factors to address indirect sources that others leave out. Some examples follow.

The FEA/USDA (1976) published a database of agricultural production and (direct) energy consumption for each of the 50 states. Efficiency of energy use in crop production was studied by Herendeen (1973). Fluck et al. (1992) developed an energy consumption model for 60 agricultural systems in Florida. Other regional and national agricultural energy studies have been published (reviewed in Smil 1990).

Peters et al. (1981) reported an output/input energy ratio of 2.6 for electricity from forest residues in Canada. This ratio increased to 6.9 when generated electricity used in the co-generation power plant was subtracted as inputs. Marks (1990) reported favorable economic and energy returns on investment for using wood powder as a fuel in district heating plants in Sweden. Hetz and Sonesson (1993) reported an output/input ratio of 7.4 for grass production and 2.9 for biogas. Detailed studies of short-rotation willow plantations for fuelwood production calculate an output/input ratio of 19.3 (Sonesson 1993). This study is compared with an emergy analysis of willow production undertaken in this dissertation.

Herendeen and Brown (1987) summarize four earlier net energy studies of woody biomass production. Output/input ratios for harvested biomass increased from 12 to 22 as rotation ages increased from 6 (*Eucalyptus* spp.) to 15 years (*Populus* spp.). When fertilization and artificial drying of the woodfuel was included, the respective ratios declined to 2.5 to 3.4. The author's analyses of 3 mixed hardwood and 2 pine forests under rotations between 30 and 120 years in southern Illinois calculated energy output/input ratios from 36.9 (for 120 year old mixed hardwoods) to 43.4 (30 year old pine), declining with rotation age. Comparing the two sets of analyses, however, Herendeen and Brown (1987) concluded that their calculation of energy ratio (i.e., output/input ratio) increases with rotation age (this study is re-evaluated using emergy analysis and the results are compared in the discussion section of this dissertation).

Hall et al. (1986) document declining energy return on investment (EROI) for domestic and imported natural gas and liquid petroleum during this century. Using input-output techniques, Cleveland and Costanza (1984) report net energy yield ratios of 2 and lower for recovered geo-pressured gas in the Gulf Coast region of the U.S. Much higher net yields were measured for natural gas and from gasification of coal.

Previous Net Emergy Studies of Biomass and Fuels

Odum (1984) overviews emergy analysis applied to agroforest systems. Early studies include an evaluation of energy alternatives for the U.S. (Odum et al. 1976);

Swaney's (1978) evaluation of climatic inputs to agriculture; a study of agricultural and natural systems in Gotland, Sweden (Jansson and Zucchetto 1978); and evaluations of plantation pine in New Zealand (Odum and Odum 1979) and ethanol from sugar cane in Brazil (Odum and Odum 1984).

Studies of agricultural production systems generally indicate high emergy investments and low emergy yield ratios. Brown and McClanahan (1992) documented a reduction in the emergy yield ratio of Thailand rice from 3.9 to 1.5 with increasing industrialization. King (1991) calculated an emergy yield ratio of 1.1 for industrial corn and commented that the ratio would be reduced if aquifer recharge were accounted for. Odum (1984) argued that agricultural crops have lower net emergy, more similar to industrial and manufactured products, and cannot replace current fossil fuels or woody biomass fuels which have higher emergy yield ratios.

Wood fuels and forests have been variously studied to date. Sundberg et al. (1991) calculated an emergy yield ratio of 22 for 18th century charcoal production from wood. Comar (1993) tracked emergy requirements for logging and wood products industries in the central Amazon. An earlier study of the Amazon and a wood-fueled electricity plant in Jari (Odum et al. 1986) calculated an emergy yield ratio of 12 for old growth logs. Alternative treatments for pulp mill effluent were studied by Keller (1992). Hookous (1995) evaluated the lumber and construction industry in the U.S. Odum (1995b) reported emergy-based options for tropical forests.

Brown et al. (1995) evaluated alternative energy options for primary use and transportation for Florida. Emergy yield ratios for non-renewable fossil fuels range from 12.5 for coal production in New Zealand (Odum and Odum 1979) to 0.03 for shale oil in Colorado (Gardner 1977; Odum 1995a). Brown et al (1993) calculated an emergy yield ratio of 11 for Alaskan oil. King and Schmandt (1991) reported yield ratios of 10.3 for onshore natural gas, 6.8 for offshore gas, 4.7 for coal methanol and 3.2 for crude oil in Texas.

Since electric power requires more transformation than most fuels, net emergy yield of electric power is usually less than that for fuels. For example, an emergy yield ratio for lignite-fired electricity measured 2.2 (Odum et al. 1987). Electricity from solar voltaic power had a yield ratio less than unity (King and Schmandt 1991).

Forest Systems Evaluated in This Study

Physical and environmental measurements of the agroforest ecosystems evaluated in this study are given in Table 3, ordered by rotation age (i.e., cycle time). Production and stored biomass are given as well as mean quantities harvested per hectare per rotation period. Energy content and specific density for woody biomass are used to convert mass and volume biomass estimates to energy units. These parameters along with rainfall and estimates of evapotranspiration form the database for evaluations of forest production and storage. Other site specific management and resource-use data are detailed individually for each system evaluation.

Systems range latitudinally from boreal forests in Sweden to tropical forests in Papua New Guinea. Cycle times range from 4 and 6 year rotation schedules for fuelwood plantations to 200 and 300 year old growth forests under natural rotations. Brief descriptions are given next for major agroforests studied here, with emphasis

Table 3. Summary of data characterizing agro-forest ecosystems evaluated in this study.

Note	Forest type	Location	Rotation age (yrs)	Above ground production (tons/ha/yr)	Above ground biomass (tons/ha)	Harvested biomass (tons/ha)	Energy content (E+4 J/g)	Wood density (tons/m3)	Rainfall (m/yr)	ET (m/yr)
1.	Willow plantation	Sweden	4.2	11.50	48.0	45.6	1.950	0.40	0.80	0.39
2.	Fuelwood plantation	Florida	5	13.01	65.0	61.8	1.674	0.34	1.32	1.03
3.	Eucalyptus plantation	Thailand	5.8	10.20	60.7	57.8	1.620	0.34	1.56	1.22
4.	Siris plantation	Puerto Rico	11	10.40	82.5	72.6	1.674	0.58	1.02	1.60
5.	Southern slash pine	Florida	25	9.60	157.8	59.5	1.884	0.70	1.32	1.03
6.	Tropical palm forest	Puerto Rico	27	19.50	199.1	---	1.633	0.50	3.70	0.83
7.	Temperate loblolly pine	Illinois	30	8.83	265.0	136.5	2.001	0.47	1.07	0.68
8.	Guanica tropical dry forest	Puerto Rico	47	6.90	45.0	---	1.674	0.70	0.80	0.72
9.	Tropical lowland tabonuco	Puerto Rico	59	10.50	197.9	---	1.674	0.60	3.00	1.76
10.	Temperate mixed hardwoods	Illinois	60	3.77	226.0	116.4	1.821	0.58	1.07	0.68
11.	Tropical premontane colorado	Puerto Rico	62	7.60	135.8	---	1.674	0.53	4.00	0.83
12.	Managed spruce/pine	Sweden	80	3.82	102.0	76.5	2.052	0.43	0.80	0.39
13.	Temperate mixed hardwoods	Illinois	80	3.55	284.0	151.2	1.821	0.58	1.07	0.68
14.	Temperate loblolly pine	Illinois	90	5.83	525.0	279.9	2.001	0.47	1.07	0.68
15.	Northern mixed coniferous	Sweden	100	3.19	120.3	80.6	2.052	0.43	0.80	0.39
16.	Temperate mixed hardwoods	Illinois	120	3.12	374.0	199.2	1.821	0.58	1.07	0.68
17.	Tropical lowland rainforest	Papua New Guinea	140	29.20	380.0	148.0	2.001	0.80	3.73	2.24
18.	Tropical cloud forest	Puerto Rico	172	3.70	82.9	---	1.674	0.70	4.50	0.16
19.	Old growth spruce	Sweden	200	1.20	188.0	112.8	2.052	0.47	0.80	0.39
20.	Tropical lowland rainforest	Brazil	300	18.57	350.0	261.5	2.001	0.80	2.30	1.10

Sources are given as footnotes to evaluation tables.

placed on forests of Sweden and Puerto Rico, the systems visited and studied in detail. Other evaluations are drawn from current literature with citations given for each agro-forest system. Item numbers refer to Table 3.

In Puerto Rico, five tropical forest ecosystems were studied: four forest types in the Luquillo mountains of eastern Puerto Rico (reviewed in Lugo and Scatena 1995); and the dry forest of Guánica on the southwestern coast (reviewed by Murphy et al. 1995). Physical, environmental and production data are summarized in Doherty et al. (1994). Generally, as elevation increases, cloud cover, cloud water interception, annual precipitation and runoff increase while solar insolation, evapotranspiration and above ground biomass decreases. Mean age of the forest, used here as cycle time and estimated from the quotient of stored biomass to annual accumulation rates (Weaver and Murphy 1990; Doherty et al. 1994), also increases with elevation from 50 years in low elevation systems to 170 years in montane forests.

The ecosystems of Luquillo Experimental Forest, a national forest managed for research and recreation, were categorized as 4 forest types (Brown et al. 1983). The elfin cloud forest (item 18), occurring above 900 m, receives water from both rainfall and cloud interception. It has high runoff, low evapotranspiration and low annual production. The colorado forest (item 11), a premontane forest dominated by *Cyrilla racemiflora*, occupies mid-elevational areas (600-900 m). The ubiquitous palm forest (item 6), dominated by mountain palm, *Prestoea montana*, occurring in poorly drained areas at both mid and low elevations, has the highest recorded production rate among the systems in Puerto Rico, high surface water runoff and low evapo-transpiration. The lowland rainforest (item 9), a lowland forest type dominated by tabonuco, *Dacryodes excelsa*, has high production, rapid turnover and high forest evapotranspiration rates. The Guánica dry forest (item 8), lying in the rain shadow of the island's central cordillera, receives mean seasonal rainfall of less than 860 mm annually. This forest type has lower net productivity, above ground biomass and diversity than the other forest types receiving higher rainfall. These systems are used in this study as examples of mature forests under natural rotations and ones not managed for timber extraction.

In Sweden, the most common trees species are spruce (*Picea aibes*) and pine (*Pinus silvestris*) both occurring almost all over the country. Birch (*Betula* spp.) a mid successional species, is the most common deciduous tree in the country, commonly 5 to 20 percent of the standing stock in spruce/pine complexes (Kempe and von Segebaden 1990). Together, these dominant tree species compose the northern coniferous forests studied here. Above ground, annual growth ranges with increasing rainfall, mean temperature and longer growing seasons from less than 1 ton/ha/yr in northern and mountainous areas to 3-4 tons/ha/yr in southern Sweden (Eriksson and Odin 1990). Standing stock varies with location and management prescription and can range from 25 tons/ha in the far north above the Arctic Circle to 180 tons/ha in old growth stands of spruce in the south (Kempe and von Segebaden 1990). Nilsson (1990) gives a thorough overview of Sweden's forests, environmental conditions affecting production, growing stock estimates, historical and current uses, industries, and future projections.

Northern coniferous forests in southern Sweden under 3 different management prescriptions and rotation ages were analyzed in this dissertation. The most common type, managed spruce/pine stands (item 12) are harvested on average every 80 years and routinely thinned during the growth cycle. Silviculturally managed forests yield on average 3.82 tons/ha/yr above ground biomass with average standing stock just over 100 tons/ha/yr. About 75% of production is harvested. Unmanaged mixed coniferous forests (item 15), naturally self-thinned and reseeded with a higher percentage of deciduous birch, were estimated to require an additional 20 years to reach a mature steady state. Net production estimates were lower (3.19 tons/ha/yr) since more gross production is channeled into maintenance and there is lower volume of usable wood. An old growth stand of spruce (item 19; Lundmark 1990) was estimated at 200 years old with a mean biomass accrual rate, estimated as the quotient of standing stock to age, of less than 1 ton/ha/yr. These forest systems were evaluated for silvicultural and harvest requirements, and form the basis for woodfuel, pulp and paper evaluations.

Evaluations of forest rotations in the Shawnee National Forest in southern Illinois were based on an earlier analysis by Herendeen and Brown (1987). Silviculture, harvest, and production data based on yield tables, were complied for each of five forest management schemes from U.S. Forest Service data (1982). Loblolly pine (*Pinus taeda*) forests under 30 and 90 year rotation schedules (items 7 and 14, respectively) were compared with mixed hardwood forests (oak-hickory) under 60, 80 and 120 year rotation schedules (items 10, 13, and 16).

Net productivity of pine forests is greater than that of mixed hardwoods, and productivity generally increases with age. Annual production rates, estimated from harvest rates and known ratios of above ground production to harvested wood, averages 3.5 tons/ha/yr for mixed hardwoods and 7.3 tons/ha/yr for pine forests. Mean biomass harvested, including volume from thinning schedules, increases for each forest type with increasing rotation age and averaged 67% of production for both pines and mixed hardwoods. A slash pine (*Pinus elliottii*) plantation in north Florida (item 5) under 25 year rotations had higher annual production than the 30 year old stand of loblolly pine in Illinois, but a lower percentage of biomass was harvested (38% of production; Gholz et al 1986).

Two tropical forest systems were evaluated: a 140 year old lowland tropical rainforest in New Britain, Papua New Guinea (Doherty and Brown 1992) and a 300 year old rainforest in Jari, Brazil (revised from Odum et al. 1986). These systems recorded the highest rate of average annual production and largest volume of stored above ground biomass, estimated from published literature on tropical forests. Forest data in Papua New Guinea (item 17) were collected from a 20,000 ha logging operation, removing 48,000 tons of lumber quality wood per annum (Tickell personal communication 1990), averaging 148 tons/ha or just 39% of standing stock, due to difficulty of terrain and a low percentage of marketable timber (Davidson 1984). In Brazil, a 2300 ha rainforest was cleared to produce 0.61 million tons of chipped fuelwood to supply a 53 MW capacity electric plant. This amounted to 262 tons/ha woody biomass removed; an estimated 75% of standing biomass (item 20).

Four short rotation fuelwood plantations were analyzed: a willow (*Salix* spp.) plantation in southern Sweden (Doherty et al. 1993; item 1); a mixed fuelwood plantation (*Eucalyptus* spp. and *Melaleuca* spp.) in south Florida (Wang et al. 1981; item 2); a eucalyptus plantation in Thailand to supply a 25 MW capacity electric plant

(NEA/FEP 1990; item 3); and an experimental siris plantation in Puerto Rico (item 4) used to foster reforestation. Plantations were harvested on 4 to 11 year schedules yielding on average from 88-95% of above ground production. Each plantation had intensive silvicultural management including planting, fertilization, mechanical or chemical weeding, and irrigation. Plantation productivity and fuelwood yields are higher than their counter part older growth forests of the same region.

Dissertation Plan

A central theorem investigated in this dissertation is the general thermodynamic concept that net resource yield or net contribution of a production process is inherently dependent upon time of growth. Quantitative theory and assembled data from different agro-forest production systems were evaluated to determine, among other postulates, the net resource yield per cycle time of the product. Data from forest production and utilization systems in Puerto Rico, Sweden and other areas were evaluated and compared using emergy analysis techniques. General relationships of emergy yield ratio, investment ratio, maximum empower and thermodynamic minimum transformities were explored using systems evaluations and computer simulation.

Forest systems evaluated for production and harvest yields are presented first. These include northern coniferous forests in Sweden; loblolly pine and mixed hardwood forests of Illinois; slash pine stands in Florida; a secondary rainforest in Papua New Guinea. Evaluations of fuelwood plantations in Sweden, Florida, and Thailand follow next. Five natural forest ecosystems in Puerto Rico are then evaluated for biomass production and storage. Evaluations of forest multiple-uses and services are presented. Analyses of non-market services of carbon sequestration, regional water supply and reforestation are followed by analyses of woodfuel development for district heating in Sweden, of pulp and paper industries, and of tourism in a national forest of Puerto Rico. Electricity evaluations are next. Electricity generation using conventional primary fuels (4 substation generator plants in Gainesville, Florida, and 4 existing operations in Thailand) are followed by 4 examples of wood-fueled electricity production.

Computer models are presented to simulate concepts of net yield and cycle time, thermodynamic minimum transformities for forest production, and maximum empower. Emergy-based measures of value are presented to place the multiple roles of forests into the regional economy and compare with market values. The results of these analyses were then used to address public policy questions concerning energy delivery systems, sustainable uses of forest resources, and forest values. The capacity of biomass fuels to compete with existing non-renewable sources and limits for civilization after the decline of fossil fuels are discussed.

METHODS

General methods are given for evaluation of agroforest production and utilization systems, for deriving indices of comparison, and for computer simulation of a general production and yield models.

Emergy Systems Evaluations

In general, all systems were studied with similar methodology (steps A-C) each described in overview below followed by more detailed descriptions.

(A) Energy systems diagrams for each of the agroforestry and resource-use sectors studied were computer drawn as a way to gain an initial network overview, combine information of collaborators, organize data-gathering efforts, and better understand concepts, ecosystem functions and system configurations.

(B) Resource evaluation tables were set up to facilitate calculations of main sources and contributions to each system studied. Resource inputs and production yields are reported in each table in physical accounting units (tons, joules, $, etc.) and then converted to common units of solar emergy (solar emjoules) to facilitate comparisons between systems.

(C) Ratios identifying resource origins and system efficiencies, and indices relating solar emergy measurements to market economic values were calculated for each system. All measurements and resultant indices were summarized in systems diagrams accompanying each emergy evaluation table.

Energy Systems Diagramming

Using energy circuit language (Odum 1971, 1988) systems diagrams were drawn for all resource production, storage and utilization systems studied in this dissertation. The diagramming steps followed for each system are given below:

1. The boundary of the system was defined.
2. A list of important sources (external causes, energy and material factors, forcing functions) was made.
3. Considering the scale of the defined system, a list was made of principal component parts believed important.
4. A list was made of processes (flows, relationships, interactions, production and consumption processes, etc.). Both resource flows and monetary transactions were included.
5. Energy systems diagrams and models were developed using the following conventions of energy language diagramming (from Odum 1971, 1988):

   Symbols: The symbols each have rigorous energetic and mathematical meanings (Figure 2).

   System Frame: A rectangular box is drawn to represent the boundaries that were selected.

   Arrangement of Sources: Any input that crossed a boundary was identified as a source, including pure energy flows, materials, information, human services, as well as inputs that were destructive. All source inputs were given a circular symbol. Sources were arranged around the outside border from left to right in order of their solar transformities starting with sunlight on the left and information and human services on the right.

   Pathway Line: Flows were represented by lines including energy, materials and information. Money was identified with dashed lines flowing in opposite direction of energy flows.

   Outflows: Any outflow which still had available potential energy, material more concentrated than the environment, or usable information was identified as a pathway from either of the three upper system borders, but not out of the bottom of the diagram.

Degraded Energy: Energy that had lost its ability to do work according to the second law of thermodynamics was represented as pathways converging to a heat sink at the bottom center of the diagram. Included was heat energy as byproducts of processes and the dispersed energy from depreciation of storages.

Adding Pathways: Pathways added their flows when they joined or when they went into the same the storage tank. Every flow in or out of a tank must be the same type of flow and measured in the same units.

Interactions: Two or more flows that were different, but were both required for a process were drawn to an interaction symbol. The flows to an interaction were connected from left to right in order of their solar transformity. The lower transformity flow was connected to the notched left margin of the symbol.

Counterclockwise Feedbacks: High-quality outputs from consumers such as information, controls, and scarce materials were identified as reinforcement pathways fed back from right to left in the diagram. Feedbacks from right to left represented a loss of concentration because of divergence.

Material Balances: Since all inflowing materials either accumulate in system storages or flow out, each inflowing material such as water or money had outflow pathways identified and drawn.

The diagrams were then simplified through aggregation of important categories that were quantified in the emergy evaluations. A systems diagram accompanied each evaluation summarizing the computations, identifying emergy values and certain physical values for sources and resource yields and listing resource indices for each transformation step. Generally diagrams included source inputs (cross boundary flows) to be evaluated including environmental inflows (sun, wind, rain, rivers, and geological processes, etc.); economically derived resources (fuels, minerals, electricity, foods, fiber, wood); human labor and indirect services; monetary exchanges; and information flows. Export flows were also drawn. Components inside the system boundary included: the main land use areas; large storages of fuel, water, and soil; the main economic interfaces with environmental resources; and final consumers. Interior circulation of money was not drawn, but all the major flows of money in and out of systems were included.

Emergy Evaluation Tables

All systems studied were analyzed using emergy evaluation tables with calculations of inputs and summaries of solar emergy indices given as footnotes. Each table was presented similarly, with 5 columns, each with the following headings:

1 Footnote	2 Item	3 Resource units (J, g, $)	4 Solar emergy per unit (*sej*/J, *sej*/g, *sej*/$)	5 Solar emergy (*sej*)

Column One is the line item number identifying the footnote at the end of the table where the source of the raw data was cited and calculations shown.

Column Two is the name of the item being evaluated, which was also identified on the accompanying systems diagram.

Column Three contains flows or storages, given in physical units (joules, grams, or dollars) reported by industry accounting or obtained from published literature and statistical abstracts. These are reported either as average annual flows per unit volume or area or per unit output. References and calculations are identified as footnotes (column 1). For example, forest production was reported as tons or solid cubic meters per unit area per unit time (tons/ha/yr or m^3/ha/yr). Inputs such as fuel were reported as (liters/ha/yr). Inputs for other systems were evaluated per unit output such as per MWh electricity produced (J-fuel/MWh-electricity) or labor cost per ton of woodfuel produced ($/ton-wood powder). Evaluations of storages were reported per unit stored (J/ha or J/ton).

Column Four lists the solar emergy per unit for each line item used to convert physical units in column 2 to units of solar emergy. These include solar emjoules per joule, *sej*/J (i.e., solar transformity) or *sej*/gram or *sej*/dollar. These were obtained from previous, independent studies (identified in Table 2) or derived from evaluations in this study and identified as footnotes to the table.

Column Five is the solar emergy of the resource input, product or storage, measured in solar emjoules per time (*sej*/ha/yr) for emergy flows, emergy per unit output (*sej*/ton, *sej*/MWh), and emergy per unit area or volume (*sej*/ha, *sej*/ton) for storages. It is the product of columns 3 and 4. Emergy values were reported in tables and figures as either E+12 or E+18 *sej*/unit to facilitate computations and comparisons between systems.

Inputs and yields for evaluated sectors were identified on each emergy evaluation table and in the text and footnotes using a similar notation (refer to Figure 4b). Aggregations of environmental inputs were identified as (I); each set of purchased inputs associated with a particular process step (i) was summed and labeled as (F_i); yields or outputs for each transformation step (i.e. total contributions, defined as the sum of all inputs) were identified as (Y_i) for annual flows or (Q_i) for stored quantities for each transformation step. In general for all agro-forestry systems evaluated, above ground forest production was denoted (Y_1); harvested biomass (process step 2) was identified (Y_2).

Solar transformities derived from these evaluations were indexed in the tables by ST_i. This was done in order to separate referenced solar transformities derived from other studies and those that were calculated from evaluations in this study. Process step summations (I_i, F_i, Y_i) and computations of transformities (ST_i) were listed as corresponding footnotes below each table.

Renewable environmental energy sources supporting biomass production (R) were estimated from the chemical potential energy of incident rainfall, measured as Gibbs free energy of the portion of rainfall that is evapotranspired. This was a surrogate input measured to include all other renewable energies including solar insolation and kinetic wind energy which are coproducts of common global solar-based sources. Because the calculation of transformities for these coupled sources are all based on the global budget of available solar emergy, adding together their calculated emergy values would double count source inputs. Evapotranspired rainfall for all evaluated agroforest systems had the largest calculated emergy value and was used to account for all coupled environmental sources. Surface water supply, split from incident rainfall as runoff, was included in the analyses of other ecosystem services. Nonrenewable environmental sources (N) of top soil and minerals were evaluated separately.

An estimate of the emergy support base of human services was made using the emergy/money ratio for the region and year of production, multiplied by the market cost or value of a commodity or service. The money paid for machinery, fuels and other goods necessary in a production sector pays for the human services involved in the refinement, manufacture and delivery of the commodity. The emergy/money ratio was used to assign an emergy value to human services in proportion to the money paid for the service, assuming that each dollar paid for a product or service represents a proportional amount of emergy supporting the direct and indirect human labor requirements.

An average emergy base for wages earned was considered an estimate of the lifestyle support requirements of both the laborers as well as the associated human services that produce and deliver the commodities used in production. If only labor hours were known for a production sector, a solar transformity for human ergonomic work was estimated (documented in footnotes) and multiplied by metabolic expenditure to estimate the emergy supporting labor.

Resource Indices and Synthesis

From the emergy evaluation tables, comparative indices of resource origins, allocations, exchange, and relations to macro-economic valuation were calculated to draw inferences and cross-system comparisons which were used as tools for making decisions regarding energy policy and public and ecosystem welfare. These measures included: net emergy yield, emergy yield ratio (YR), emergy investment ratio (IR), emergy exchange ratio (ER), environmental loading ratio, emergy/monetary cost ratio (i.e., emergy/dollar ratio) and the emdollar value of resources (refer to Table 1 and Figure 4 for definitions).

The emdollar values (em$) for current year of production for resources or ecosystem services were calculated as a biophysical estimate of macro-economic (public policy) value. This measure is an estimate of the portion of gross economic product for a region attributed to the resource or service (Table 1). The emdollar value was compared with market values of forest products and with other estimates of marco-economic value for non-market forest commodities and services.

Relationships and trends of production rates, investments, net yields, transformities and replacement time derived from the emergy evaluations were graphed as simple regressions addressing hypotheses. Together, resource indices, emergy summations, and graphical analyses were used to synthesize evaluations and discuss alternatives regarding forest resource-use and energy policy.

Computer Simulation

Computer models were developed to investigate general ecosystem principles regarding the relationship of forest turnover rates and indices of net emergy yield and investment. Empirical data from emergy evaluations of forest systems and from literature sources were used to test hypotheses and verify thermodynamic relationships evidenced from the analyses. Energy circuit language and the resulting system diagrams were mathematically defined with differential equations drawn from the model configuration, orientation of components and the relationships identified in the diagrams (Odum 1983).

Conceptual models were drawn, state variables were identified, and mathematical expressions were written for interactions and processes. Models were calibrated using data from the analysis of silviculturally grown spruce/pine forests. Using spreadsheet iterations, steady state values were determined for above ground biomass of a mature forest and coefficients were calculated for each interactive pathway (i.e., mathematical expressions identifying relationships of two or more state variables over time).

Equations were then written into BASIC computer language and simulated to investigate changes over time with changes in inputs or state variables using the constructed computer program. By first identifying the baseline calibration at steady state, the effects of changes in system configuration could be investigated by changing one variable at a time in the program. Graphs were obtained from the computer simulations to illustrate general principles of forest production, turnover and net yield.

RESULTS

Emergy systems evaluation of forests and their utilization are given next including carbon sequestration, biomass storage, water supply, recreation, and production of market commodities of lumber, pulp, paper and fuelwood. Net emergy evaluations of electricity generation alternatives follow.

Emergy Evaluation of Forest Productivity and Extraction

Forests of Southern Sweden

Boreal spruce/pine forests in southern Sweden were evaluated for silvicultural production and timber harvest (Table 4). Under 80 year rotation schedules, about 75% of average above ground production (3.82 tons/ha/yr) is harvested annually. Environmental sources accounted for 92% of inputs to silvicultural production. Economic sources (F_1 and F_2) measured 40% of inputs to harvested biomass. A solar transformity for silviculturally managed forest production (ST_1) measured 4930 sej/J, more than doubling for harvested biomass (Figure 8). The emergy yield ratio declined 80% from standing crop (YR_1) to harvested biomass (YR_2). An emergy investment ratio for harvested biomass (IR_2) measured 7 times greater than standing crop (IR_1).

Analyses were also made of 100 and 200 year old unmanaged boreal forests, naturally reseeded and self-thinned. It was estimated that an additional 20 years would

Table 4. Emergy evaluation of boreal spruce (***Picea aibes***) and pine (***Pinus silvestris***) silvicultural production and timber extraction under 80 year rotation schedules in southern Sweden.[a] Analysis is summarized in Figure 8.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[b]	Solar emergy flow (E+12 sej/ha/yr)
I	Environmental sources:			
	1. Sunlight	2.57E+13 J	1	25.7
	2. Wind, kinetic	8.73E+10 J	1500	130.9
	3. Evapo-transpired rain	1.95E+10 J	18200	355.1
F_1	Silviculture:			
	4. Motor fuel	5.59E+07 J	47900	2.7
	5. Tractors, trucks	66 g	6.7E+09	0.4
	6. Human services	18.70 $	1.5E+12	28.1
	Y_1 Above ground production (3.82 tons/ha/yr)	7.84E+10 J	ST_1	386.3
F_2	Harvesting:			
	7. Motor fuel	5.97E+08 J	47900	28.6
	8. Feller, forwarder	188 g	6.7E+09	1.3
	9. Human services	101.26 $	1.5E+12	151.9
	10. Capital investment	14.44 $	1.5E+12	21.7
	Y_2 Harvested biomass (2.85 tons/ha/yr)	5.85E+10 J	ST_2	589.7

Summary of measurements:

Solar transformity:			
ST_1	Above ground production	4928	sej/J
ST_2	Harvested biomass	10,083	sej/J
Emergy yield ratio:			
YR_1	Above ground production	12.39	
YR_2	Harvested biomass	2.51	
Emergy investment ratio:			
IR_1	Above ground production	0.09	
IR_2	Harvested biomass	0.66	

Table 4--continued; notes.

a. Analysis based on an average spruce/pine forest production of 8.989 m^3/ha/yr, harvesting 74.6% of production (6.704 m^3/ha/yr) in southern Sweden (based on an 80 year, steady state rotation) (Doherty et al. 1993).

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported as mass use *sej*/g; monetary inputs use *sej*/\$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

I Environmental inputs:

1. Solar energy = (area) (avg insolation) (1-albedo) = (10,000 m^2/ha) (85.4 kcal/cm^2/yr) (10,000 cm^2/m^2) (4186 J/kcal) (1 - 0.28) = 2.57E+13 J/ha/yr

2. Wind, kinetic energy = (Vertical gradient of wind)^2 (hgt of atmospheric boundary) (density of air) (eddy diffussion coefficient) (1 ha) (sec/yr) = [(3.0 m/s) / (1000 m)]^2 (1000 m) (1.23 kg/m^3) (25 m^2/sec) (10,000 m^2/ha) (3.154E+7 sec/yr) = 8.73E+10 J/ha/yr

3. Rain, chemical potential energy = (area) (rainfall) (% evapotrans) (Gibbs free energy) = (10,000m^2/ha) (0.80m) (0.49) (1000 kg/m^3) (4.94E+3 J/kg) = 1.95E+10 J/ha/yr

F_1 Inputs to silvicultural management:

	fuel (liters/ha/yr)	machines (g/ha/yr)
scarification:	0.28	19.0
planting:	0.04	3.5
stand regulation:	0.35	8.8
ditching:	0.52	3.4
roads:	0.38	31.7
Total:	1.57 l/ha/yr	66.4 g/ha/yr

4. Motor fuel = (1.57 liters/ha/yr) (35.6E+6 J/l) = 5.59E+7 J/ha/yr

5. Machinery depreciation [given as %wgt (g)] = (0.1 operating hrs/ha/yr) / (15,000 hrs useful life) (10 ton trucks, tractors) (1E+6 g/ton) = 66.4 g/ha/yr

6. Human services (total cost of production) = (13.52 SEK/m^3) (8.989 m^3/ha/yr) / (6.50 SEK/\$US, 1988) = 18.70 \$/ha/yr

Y_1 Above ground production = (9.0 m^3/ha/yr) (0.425E+6 g/m^3) (2.052E+4 J/g) = 7.84E+10 J/ha/yr

F_2 Harvesting:

7. Motor fuels = (2.5 liters/m^3) (6.704 m^3/ha/yr) (35.6E+6 J/liter) = 5.97E+08 J/ha/yr

8. Feller and forwarder depreciation [given as %wgt. (g)]: (0.07 operating hrs/m^3) / (15,000 hrs useful life) (6 tons) (1E+6 g/ton) (6.704 m^3/ha/yr) = 187.71 g/ha/yr

9. Human services = [(Direct costs 85.6 SEK/m^3) - (silv. prod. costs 13.5 SEK/m^3)] + (indirect costs 12.1 SEK/m^3) + (depreciation 14.0 SEK/m^3) = (98.2 SEK/m^3) (6.7 m^3/ha/yr) / (6.50 SEK/\$US, 1988) = 101.26 \$/ha/yr

10. Capital cost of machines = (6.7 m^3/ha/yr harvest) (0.07 hrs/m^3) (0.47 hrs/ha/yr) (200.0 SEK/hr capital costs) = (93.9 SEK/ha/yr) / (6.50 SEK/\$US, 1988) = 14.44 \$/ha/yr

Y_2 Harvested biomass: (harvested stemwood, 5.6 m^3/ha/yr +1/2 of logging residues, 1.12 m^3/ha/yr) = 6.7 m^3/ha/yr (0.425E+6 g/m^3) (2.052E+4 J/g) = 5.85E+10 J/ha/yr

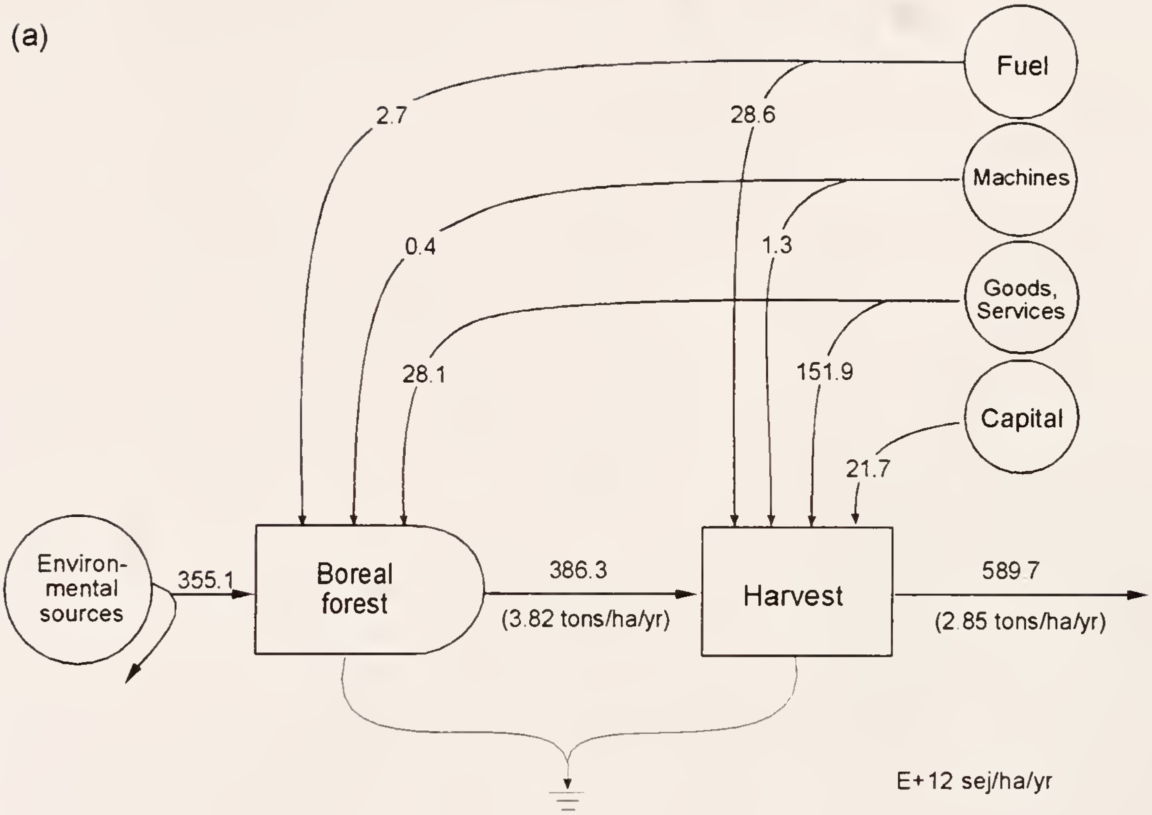
Table 4--continued.

Summary of measurements:
I Item 1 = 355.14E+12 sej/ha/yr
F_1 Items 4+5+6 = 31.17E+12 sej/ha/yr
F_2 Items 7+8+9+10 = 203.50E+12 sej/ha/yr
Y_1 I+F_1 = 386.30E+12 sej/ha/yr
Y_2 I+F_1+F_2 = 589.70E+12 sej/ha/yr

Solar transformities = Y_i (sej/ha/yr) / Y_i (J/ha/yr):
ST_1 Above ground production = (3.86E+14 sej/ha/yr) / (7.84E+10 J/ha/yr) = 4928 sej/J
ST_2 Harvested biomass = (5.65E+14 sej/ha/yr) / (5.85E+10 J/ha/yr) = 10,083 sej/J

Emergy yield ratio = Y_i / (F_1+... F_i):
YR_1 Above ground production = (386.30E+12 sej/ha/yr) / (31.17E+12 sej/ha/yr) = 12.39
YR_2 Harvested biomass = (589.70E+12 sej/ha/yr) / (31.17 +179.07)E+12 sej/ha/yr = 2.51

Emergy investment ratio = (F_1+... F_i) / I:
IR_1 Above ground production = (31.17E+12 sej/ha/yr) / (355.1E+12 sej/ha/yr) = 0.09
IR_2 Harvested biomass = (31.17 + 203.50)E+12 sej/ha/yr / (355.1E+12 sej/ha/yr) = 0.66



(b)

	Above ground production	Harvested biomass
Solar transformity	4928 sej/J	10,083 sej/J
Emergy yield ratio	12.39	2.51
Emergy investment ratio	0.09	0.66

Figure 8. Systems diagram of boreal spruce/pine silvicultural forest production and timber extraction under 80 year rotation schedules in southern Sweden: (a) solar emergy flows; (b) resource indices. Refer to Table 4 for calculations.

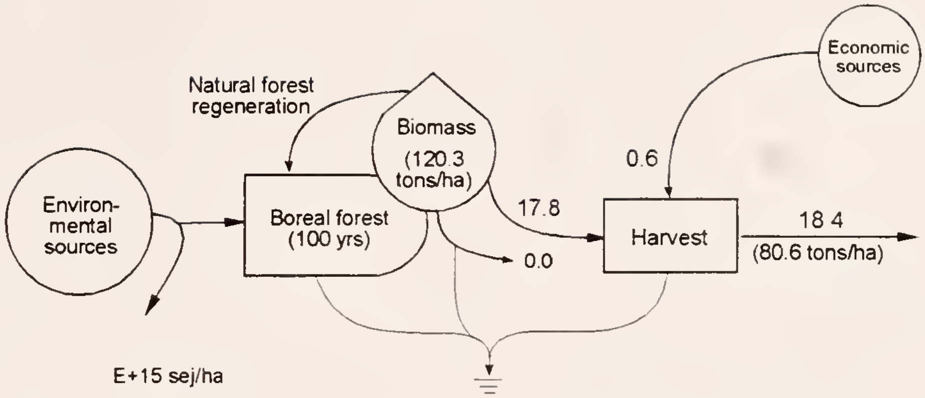
be necessary for forests in southern Sweden to mature after clear cutting if no planting or silviculture was applied (Figure 9a). While approximately 75% of annual above ground production is harvested in managed forests, only 67% of stored biomass (Q_1 = 120 tons/ha) is harvested (Q_2 = 80.6 tons/ha) in natural forests due to a higher percentage of dead and diseased wood. Solar transformities for stored and harvested biomass were both higher in unmanaged forests than in managed stands due to 20 additional years of environmental emergy sequestered through production (Figure 9a). Harvest emergy, 71.4E+12 sej/ton, measured 3% of total inputs. An emergy yield ratio of 4.1 for harvested biomass was 1.6 times greater than the emergy yield ratio for harvested biomass from managed stands.

Two-hundred year old growth spruce ecosystems with 188.0 tons/ha above ground biomass had the largest solar transformity measuring 9573 sej/J, almost twice that for biomass production in managed stands (Figure 9b). It was assumed that usable wood from old growth averaged ten percent lower (60% compared with 67% for younger forests) yielding 112.8 tons/ha stemwood. Higher emergy yield ratios and lower investment ratios indicate the surplus of environmental sources used in storing biomass under longer turnover periods.

Forests of Southern Illinois

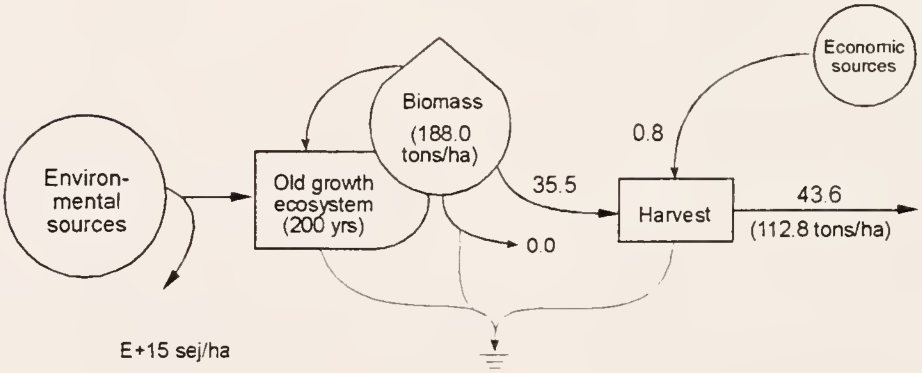
Five forest ecosystems in southern Illinois under different management schedules were compared for annual production rates, silviculture and harvest emergy expenditures (Table 5). Using data from Herendeen and Brown (1987), loblolly pine forest production under 30 and 90 year rotations are compared with mixed hardwood

(a)



	Above ground biomass	Harvested biomass
Solar transformity	7188 sej/J	14,243 sej/J
Emergy yield ratio	—	4.09
Emergy investment ratio	—	0.32

(b)



	Above ground biomass	Harvested biomass
Solar transformity	9200 sej/J	18,778 sej/J
Emergy yield ratio	—	5.41
Emergy investment ratio	—	0 23

Figure 9. Systems diagrams of unmanaged forest production in northern coniferous ecosystems of southern Sweden: (a) self-thinned, natural mixed coniferous forest regeneration, 100 years old; (b) old growth spruce forest, 200 years old. Calculations given as footnotes.

Figure 9--continued; notes.

Naturally regenerated forests:

Q_1 Above ground biomass of mature forest = 283 m^3/ha (mean stand volume in southern Sweden; Nilsson personal communication): (283 m^3/ha) (0.425 tons/m^3) = 120.3 tons/ha (1E+6 g/ton) (2.052E+4 J/g) = 2.47E+12 J/ha

Q_2 Harvested biomass: utilized wood volume in self-thinned, unmanaged forests is about 89% of silviculturally managed stands (Vikinge 1991) of which 75% of standing crop is harvested (Table 4), therefore 67% of production is est. harvested; (120.3 tons/ha; Q_1 above) (67%) = 80.6 tons/ha (1E+6 g/ton) (2.052E+4 J/g) = 1.65E+12 J/ha

I Environmental sources = (355.1E+12 sej/ha/yr; Table 4) (100 yr. rotation) (est. 50% used) = 1.78E+16 sej/ha

F_2 Harvest subsidies = (203.5E+12 sej/hayr) / (2.85 tons/ha/yr harvested; Table 4) = 71.42E+12 sej/ton (80.6 tons/ha harvested) = 5.76E+15 sej/ha

ST_1 Solar transformity for Q_1 = (1.78E+16 sej/ha) / (2.47E+12 J/ha) = 7188 sej/J

ST_2 Solar transformity for Q_2 = [(17.8 + 5.76)E+15 sej/ha] / (1.65E+12 J/ha) = 14,243 sej/J

YR_2 Emergy yield ratio for $Q_2 = (I + F_2) / F_2$ = (2.36E+16 sej/ha) / (5.76E+15 sej/ha) = 4.09

IR_2 Emergy investment ratio for $Q_2 = F_2 / I_2$ = (5.76E+15 sej/ha) / (1.78E+16 sej/ha) = 0.32

Old growth forests:

Q_1 Above ground biomass for old growth forest = 400 m^3/ha (Lundmark 1990): (400 m^3/ha) (0.470 tons/m^3; Danielsson personal communication) = 188.0 tons/ha (1E+6 g/tons) (2.052E+4 J/g) = 3.86E+12 J/ha

Q_2 Harvested biomass: (60% harvested; est. 10% lower than percent vol. harvested in 100 year old stand); (188.0 tons/ha) (60%) = 112.8 tons/ha (1E+6 g/ton) (2.052E+4 J/g) = 2.32E+12 J/ha

I Environmental sources = (355.1E+12 sej/ha/yr; Table R-1) (200 yr. turnover time) (est. 50% used) = 3.55E+16 sej/ha

F_2 Harvest subsidies = (71.42E+12 sej/ton) (112.8 tons/ha harvested) = 8.06E+15 sej/ha

ST_1 Solar transformity for old growth biomass (Q_1) = (3.55E+16 sej/ha) / (3.86E+12 J/ha) = 9200 sej/J

ST_2 Solar transformity for harvested old growth (Q_2) = [(35.51 + 8.06)E+15 sej/ha] / (2.32E+12 J/ha) = 18,778 sej/J

YR_2 Emergy yield ratio for $Q_2 = (I + F_2) / F_2$ = (4.36E+16 sej/ha) / (8.06E+15 sej/ha) = 5.41

IR_2 Emergy investment ratio for $Q_2 = F_2 / I_2$ = (8.06E+15 sej/ha) / (3.55E+16 sej/ha) = 0.23

Table 5. Emergy evaluations of typical loblolly pine and mixed hardwood forest production and timber extraction under different rotation schedules in Shawnee National Forest, southern Illinois. Values are E+12 sej/ha/yr; values in parentheses are average tons/ha/yr. Resource units and emergy calculations are given as footnotes for each rotation. Analyses are summarized in Figure 10.

Note	Item	Loblolly pine 30 years[a]	 90 years[b]	Mixed hardwoods 60 years[c]	 80 years[d]	 120 years[e]
I	Environmental sources:	614.0	614.0	614.0	614.0	614.0
F_1	Silviculture, management:					
	1. Minimum level mgt.	24.4	24.4	24.4	24.4	24.4
	2. Road maintenance	14.8	14.8	14.8	14.8	14.8
	3. Site preparation fuels	16.3	5.4	5.4	4.0	2.7
	4. Site prepartion services	44.1	14.7	14.6	10.9	7.3
	5. Fertilization	7.5	0	0	0	0
	6. Commercial thinning	0	11.4	2.1	3.5	2.8
Y_1	Above ground production	721.0	685.0	675.0	671.0	666.0
	(tons/ha/yr)	(8.83)	(5.83)	(3.77)	(3.55)	(3.12)
F_2	Harvesting:					
	7. Fuels	24.0	25.3	12.1	13.1	11.3
	8. Machinery	3.7	3.9	1.5	1.7	1.4
	9. Labor	249.0	262.0	125.0	136.0	117.0
	10. Harvest preparation	8.0	8.0	8.0	8.0	8.0
Y_2	Harvested biomass	1010.0	983.0	822.0	830.0	803.0
	(tons/ha/yr)	(4.55)	(4.78)	(2.29)	(2.48)	(2.14)
Summary of measurements:						
Solar transformity (sej/J):						
ST_1	Above ground production	4,075	5,863	9,834	10,399	11,740
ST_2	Harvested biomass	11,043	10,272	19,697	18,383	20,645
Emergy yield ratio:						
YR_1	Above ground production	6.74	9.68	11.03	11.65	12.81
YR_2	Harvested biomass	2.57	2.66	3.95	3.84	4.24
Emergy investment ratio:						
IR_1	Above ground production	0.17	0.12	0.10	0.09	0.08
IR_2	Harvested biomass	0.64	0.60	0.34	0.35	0.31

Table 5--continued; notes.

Data compiled from Herendeen and Brown (1987) unless cited otherwise in footnote calculations. Wood characteristics and production quantities are reported as follows:

	Forest type	Rotation period (years)	Wood density (tons/m^3)	Energy content (E+6 kcal/ton)	Above ground biomass (tons/ha/rotation)	Harvest yield (tons/ha/rot.)	Thinning yield (tons/ha/rot.)
a.	Loblolly pine	30	0.47	4.78	265	136.5	0.0
b.	Loblolly pine	90	0.47	4.78	525	279.9	150.7
c.	Mixed hardwood	60	0.58	4.35	226	116.4	21.1
d.	Mixed hardwood	80	0.58	4.35	284	151.2	47.1
e.	Mixed hardwood	120	0.58	4.35	374	199.2	57.2

I. Evapo-transpired rain [assumed same for all forest rotations]: (42 in/yr; NOAA 1977) (64% ET; est. using DeAngelis et al. 1981) (25.4 mm/in) / (1000 mm/m) (1E+4 m^2/ha) (1000 kg/m^3) (4.94E+3 J/kg) = 3.37E+10 J/ha/yr (18200 sej/J) = 6.14E+14 sej/ha/yr

F_1 Silviculture:

1. Minimum level management, maintenance [reported same for all forest rotations]: 6.09 \$/ha/yr (4.0E+12 sej/\$, U.S. 1978; Odum 1994) = 2.44E+13 sej/ha/yr

2. Road maintenance [reported same for all forest rotations]: 3.71 \$/ha/yr (4.0E+12 sej/\$, U.S. 1978) = 1.48E+13 sej/ha/yr

3. Site preparation fuels:
   a. (2.43E+6 kcal/ha/rotation) (4186 J/kcal) / (30 yr. rotation) = 3.40E+08 J/ha/yr (47900 sej/J) = 1.63E+12 sej/ha/yr
   b. (2.43E+6 kcal/ha/rotation) (4186 J/kcal) / (90 yr. rotation) = 1.13E+08 J/ha/yr (47900 sej/J) = 5.42E+12 sej/ha/yr
   c. (1.16E+6 kcal/ha/rotation) (4186 J/kcal) / (60 yr. rotation) = 1.12E+08 J/ha/yr (47900 sej/J) = 5.38E+12 sej/ha/yr
   d. (1.16E+6 kcal/ha/rotation) (4186 J/kcal) / (80 yr. rotation) = 8.42E+07 J/ha/yr (47900 sej/J) = 4.04E+12 sej/ha/yr
   e. (1.16E+6 kcal/ha/rotation) (4186 J/kcal) / (120 yr. rotation) = 5.62E+07 J/ha/yr (47900 sej/J) = 2.69E+12 sej/ha/yr

4. Site prepartion services:
   a. (330.91 \$/ha/rotation) / (30 yrs) = 11.03 \$/ha/yr (4.0E+12 sej/\$, U.S 1978; Odum 1995) = 4.41E+13 sej/ha/yr
   b. (330.91 \$/ha/rotation) / (90 yrs) = 3.68 \$/ha/yr (4.0E+12 sej/\$) = 1.47E+13 sej/ha/yr
   c. (218.88 \$/ha/rotation) / (60 yrs) = 3.65 \$/ha/yr (4.0E+12 sej/\$) = 1.46E+13 sej/ha/yr
   d. (218.88 \$/ha/rotation) / (80 yrs) = 2.74 \$/ha/yr (4.0E+12 sej/\$) = 1.09E+13 sej/ha/yr
   e. (218.88 \$/ha/rotation) / (120 yrs) = 1.82 \$/ha/yr (4.0E+12 sej/\$) = 7.30E+13 sej/ha/yr

5. Fertilization [only applied on loblolly pine forests of 30 year rotations]:
   a. (2.72E+06 J/ha/rotation) / (30 yrs) / (5. 83E+04 J/kg) (1000 g/kg) = 1.55E+3 g/ha/yr (4.8E+9 sej/J) = 7.45E+12 sej/ha/yr

6. Commercial thinning [volume wood harvested from thinning operations are given in Y_2 below]:
   a. No thinning applied.

Table 5--continued.

b. (1.60E+04 kcal/m^3) (4186 J/kcal) (320.60 m^3/ha/rotation) / (90 yrs) = 2.39E+08 J/ha/yr (47900 sej/J) = 1.14E+13 sej/ha/yr

c. (1.70E+04 kcal/m^3) (4186 J/kcal) (36.40 m^3/ha/rotation) / (60 yrs) = 4.32E+07 J/ha/yr (47900 sej/J) = 2.07E+12 sej/ha/yr

d. (1.70E+04 kcal/m^3) (4186 J/kcal) (81.20 m^3/ha/rotation) / (80 yrs) = 7.22E+07 J/ha/yr (47900 sej/J) = 3.46E+12 sej/ha/yr

e. (1.70E+04 kcal/m^3) (4186 J/kcal) (98.70 m^3/ha/rotation) / (120 yrs) = 5.85E+07 J/ha/yr (47900 sej/J) = 2.80E+12 sej/ha/yr

Y_1 Above ground production [estimates by Herendeen and Brown (1987) using known ratios of above ground biomass to harvested wood as follows: 1.94 * (harvested biomass, Y_2 below) for rotations 30-60 yrs; and 1.88 for rotations > 90 yrs]:

a. (1.94) (136.5 tons/ha/rotation) = 265 tons/ha/rotation / (30 yrs) = 8.83 tons/ha/yr (4.78E+06 kcal/ton) (4186 J/kcal) = 1.77E+11 J/ha/yr

b. (1.88) (279.9 tons/ha/rotation) = 525 tons/ha/rotation / (90 yrs) = 5.83 tons/ha/yr (4.78E+06 kcal/ton) (4186 J/kcal) = 1.17E+11 J/ha/yr

c. (1.94) (116.4 tons/ha/rotation) = 226 tons/ha/rotation / (60 yrs) = 3.77 tons/ha/yr (4.35E+06 kcal/ton) (4186 J/kcal) = 6.86E+10 J/ha/yr

d. (1.88) (151.2 tons/ha/rotation) = 284 tons/ha/rotation / (80 yrs) = 3.55 tons/ha/yr (4.35E+06 kcal/ton) (4186 J/kcal) = 6.86E+10 J/ha/yr

e. (1.88) (199.1 tons/ha/rotation) = 374 tons/ha/rotation / (120 yrs) = 3.12 tons/ha/yr (4.35E+06 kcal/ton) (4186 J/kcal) = 5.67E+10 J/ha/yr

F_2 Harvesting:

7. Fuel use: Medium skidder, 17,158 kcal/ton + Chain saw, 9167 kcal/ton = 26,325 kcal/ton

a. (26,325 kcal/ton) (4.55 tons/ha/yr) (4186 J/kcal) = 5.01E+08 J/ha/yr (47900 sej/J) = 2.40E+13 sej/ha/yr

b. (26,325 kcal/ton) (4.78 tons/ha/yr) (4186 J/kcal) = 5.27E+08 J/ha/yr (47900 sej/J) = 2.53E+13 sej/ha/yr

c. (26,325 kcal/ton) (2.29 tons/ha/yr) (4186 J/kcal) = 2.53E+08 J/ha/yr (47900 sej/J) = 1.21E+13 sej/ha/yr

d. (26,325 kcal/ton) (2.48 tons/ha/yr) (4186 J/kcal) = 2.73E+08 J/ha/yr (47900 sej/J) = 1.31E+13 sej/ha/yr

e. (26,325 kcal/ton) (2.14 tons/ha/yr) (4186 J/kcal) = 2.35E+08 J/ha/yr (47900 sej/J) = 1.13E+13 sej/ha/yr

8. Machinery depreciation [given as % wt. (g)]:
Tractor: (0.08 hrs/m^3) / (12,000 hr. life expectancy) (8 ton) (1E+6 g/ton) = 53.33E+4 g/m^3
Chainsaw: (0.33 hrs/m^3) / (2000 hr. life expectancy) (45 lbs, est. wt.) (453.6 g/lb) = 3.37 g/m^3

a. Tractor: (53.3 g/m^3) / (0.47 tons/m^3, wood density) (4.55 tons/ha/yr, harvest) = 524 g/ha/yr
Chainsaw: (3.37 g/m^3) / (0.47 tons/m^3) (4.55 tons/ha/yr) = 33 g/ha/yr
Total depreciation = (524 + 33) g/ha/yr = 556 g/ha/yr (6.7E+9 sej/J) = 3.73E+12 sej/ha/yr

b. Tractor: (53.3 g/m^3) / (0.47 tons/m^3) (4.78 tons/ha/yr) = 551 g/ha/yr
Chainsaw: (3.37 g/m^3) / (0.47 tons/m^3) (4.78 tons/ha/yr) = 34 g/ha/yr
Total depreciation = (551 + 34) g/ha/yr = 585 g/ha/yr (6.7E+9 sej/J) = 3.92E+12 sej/ha/yr

c. Tractor: (53.3 g/m^3) / (0.58 tons/m^3) (2.29 tons/ha/yr) = 214 g/ha/yr
Chainsaw: (3.37 g/m^3) / (0.58 tons/m^3) (2.29 tons/ha/yr) = 13 g/ha/yr
Total depreciation = (214 + 13) g/ha/yr = 227 g/ha/yr (6.7E+9 sej/J) = 1.52E+12 sej/ha/yr

d. Tractor: (53.3 g/m^3) / (0.58 tons/m^3) (2.48 tons/ha/yr) = 231 g/ha/yr
Chainsaw: (3.37 g/m^3) / (0.58 tons/m^3) (2.48 tons/ha/yr) = 14 g/ha/yr
Total depreciation = (231 + 14) g/ha/yr = 245 g/ha/yr (6.7E+9 sej/J) = 1.65E+12 sej/ha/yr

Table 5--continued.

e. Tractor: (53.3 g/m^3) / (0.58 $tons/m^3$) (2.14 tons/ha/yr) = 199 g/ha/yr
Chainsaw: (3.37 g/m^3) / (0.58 $tons/m^3$) (2.14 tons/ha/yr) = 13 g/ha/yr
Total depreciation = (199 + 13) g/ha/yr = 212 g/ha/yr (6.7E+9 sej/J) = 1.42E+12 sej/ha/yr

9. Harvest labor: 2.98 labor-hrs/ton, est. (Table 6, note 7):

Solar transformity for U.S. labor estimated as: (8.11E+24 sej/yr, U.S. 1978; Odum 1995) / (2.06E+08 people; est. population; WRI 1994) / (64.3% population between 15 and 65) / (365 d/yr) / (3200 kcal/day metabolism)/ (4186J/kcal) = 1.25E+07 sej/J

a. (2.98 hrs/ton) (4.55 tons/ha/yr; avg. harvest, Y_2 below) (350 kcal/labor-hr, energy expenditure; Sundberg and Silversides 1988) (4186 J/kcal) = 1.99E+07 J/ha/yr (1.25E+07 sej/J) = 2.49E+14 sej/ha/yr
b. (2.98 hrs/ton) (4.78 tons/ha/yr) (350 kcal/labor-hr) (4186 J/kcal) = 2.09E+07 J/ha/yr (1.25E+07 sej/J) = 2.62E+14 sej/ha/yr
c. (2.98 hrs/ton) (2.29 tons/ha/yr) (350 kcal/labor-hr) (4186 J/kcal) = 1.00E+07 J/ha/yr (1.25E+07 sej/J) = 1.25E+14 sej/ha/yr
d. (2.98 hrs/ton) (2.48 tons/ha/yr) (350 kcal/labor-hr) (4186 J/kcal) = 1.08E+07 J/ha/yr (1.25E+07 sej/J) = 1.36E+14 sej/ha/yr
e. (2.98 hrs/ton) (2.14 tons/ha/yr) (350 kcal/labor-hr) (4186 J/kcal) = 9.33E+06 J/ha/yr (1.25E+07 sej/J) = 1.17E+14 sej/ha/yr

10. Harvest preparation [reported same for all forest rotations]: 2.00 $/ha/yr (4.0E+12 sej/$, U.S. 1978; Odum 1995) = 8.00E+12 sej/ha/yr

Y_2 Harvested biomass:
a. Final harvest: 4.55 dry tons/ha/yr (4.78E+06 kcal/ton) (4186 J/kcal) = 9.10E+10 J/ha/yr
b. Thinning yield: (150.7 tons/ha/rotation) / (90 yrs) = 1.67 tons/ha/yr
Final harvest: (279.9 tons/ha/rotation) / (90 yrs) = 3.11 tons/ha/yr
Total biomass harvested: (1.67 + 3.11) tons/ha/yr = 4.78 tons/ha/yr
(4.78E+06 kcal/ton) (4186 J/kcal) = 9.57E+10 J/ha/yr
c. Thinning yield: (21.1 tons/ha/rotation) / (60 yrs) = 0.35 tons/ha/yr
Final harvest: (116.4 tons/ha/rotation) / (60 yrs) = 1.94 tons/ha/yr
Total biomass harvested: (0.35 + 1.94) tons/ha/yr = 2.29 tons/ha/yr
(4.35E+06 kcal/ton) (4186 J/kcal) = 4.17E+10 J/ha/yr
d. Thinning yield: (47.1 tons/ha/rotation) / (80 yrs) = 0.59 tons/ha/yr
Final harvest: (151.2 tons/ha/rotation) / (80 yrs) = 1.89 tons/ha/yr
Total biomass harvested: (0.59 + 1.89) tons/ha/yr = 2.48 tons/ha/yr
(4.35E+06 kcal/ton) (4186 J/kcal) = 4.51E+10 J/ha/yr
e. Thinning yield: (57.2 tons/ha/rotation) / (120 yrs) = 0.48 tons/ha/yr
Final harvest: (199.2 tons/ha/rotation) / (120 yrs) = 1.66 tons/ha/yr
Total biomass harvested: (0.48 + 1.66) tons/ha/yr = 2.14 tons/ha/yr
(4.35E+06 kcal/ton) (4186 J/kcal) = 3.89E+10 J/ha/yr

Summary of measurements:

a. F_1 Items 1-6 = 1.07E+14 sej/ha/yr
F_2 Items 7-10 = 2.85E+14 sej/ha/yr
ST_1 (7.21E+14 sej/ha/yr) / (1.77E+11 J/ha/yr) = 4,075 sej/J
ST_2 (1.01E+15 sej/ha/yr) / (9.10E+10 J/ha/yr) = 11,043 sej/J
YR_1 Y_1 / F_1 = (7.21E+14 sej/ha/yr) / (1.07E+14 sej/ha/yr) = 6.74

Table 5--continued

a. YR_2 $Y_2 / (F_1 + F_2)$ = (1.01E+15 sej/ha/yr) / (1.07 + 2.85)E+14 sej/ha/yr = 2.57
IR_1 F_1 / I = (1.07E+14 sej/ha/yr) / (6.14E+14 sej/ha/yr) = 0.17
IR_2 $(F_1 + F_2) / I$ = (1.07 + 2.85)E+14 sej/ha/yr / (6.14E+14 sej/ha/yr) = 0.64

b. F_1 Items 1-6 = 7.07E+13 sej/ha/yr
F_2 Items 7-10 = 2.99E+14 sej/ha/yr
ST_1 (6.85E+14 sej/ha/yr) / (1.17E+11 J/ha/yr) = 5,863 sej/J
ST_2 (9.83E+14 sej/ha/yr) / (9.57E+10 J/ha/yr) = 10,272 sej/J
YR_1 Y_1 / F_1 = (6.85E+14 sej/ha/yr) / (7.07E+13 sej/ha/yr) = 9.68
YR_2 $Y_2 / (F_1 + F_2)$ = (9.83E+14 sej/ha/yr) / (7.07 + 2.99)E+14 sej/ha/yr = 2.66
IR_1 F_1 / I = (7.07E+14 sej/ha/yr) / (6.14E+14 sej/ha/yr) = 0.12
IR_2 $(F_1 + F_2) / I$ = (7.07 + 2.99)E+14 sej/ha/yr / (6.14E+14 sej/ha/yr) = 0.60

c. F_1 Items 1-6 = 6.13E+13 sej/ha/yr
F_2 Items 7-10 = 1.47E+14 sej/ha/yr
ST_1 (6.75E+14 sej/ha/yr) / (6.86E+10 J/ha/yr) = 9,834 sej/J
ST_2 (8.22E+14 sej/ha/yr) / (4.17E+10 J/ha/yr) = 19,697 sej/J
YR_1 Y_1 / F_1 = (6.75E+14 sej/ha/yr) / (6.13E+13 sej/ha/yr) = 11.03
YR_2 $Y_2 / (F_1 + F_2)$ = (8.22E+14 sej/ha/yr) / (6.13 + 1.47)E+14 sej/ha/yr = 3.95
IR_1 F_1 / I = (6.13E+14 sej/ha/yr) / (6.14E+14 sej/ha/yr) = 0.10
IR_2 $(F_1 + F_2) / I$ = (6.13 + 1.47)E+14 sej/ha/yr / (6.14E+14 sej/ha/yr) = 0.34

d. F_1 Items 1-6 = 5.76E+13 sej/ha/yr
F_2 Items 7-10 = 1.59E+14 sej/ha/yr
ST_1 (6.71E+14 sej/ha/yr) / (6.46E+10 J/ha/yr) = 10,399 sej/J
ST_2 (8.30E+14 sej/ha/yr) / (4.51E+10 J/ha/yr) = 18,383 sej/J
YR_1 Y_1 / F_1 = (6.71E+14 sej/ha/yr) / (5.76E+13 sej/ha/yr) = 11.65
YR_2 $Y_2 / (F_1 + F_2)$ = (8.30E+14 sej/ha/yr) / (5.76 + 1.59)E+14 sej/ha/yr = 3.84
IR_1 F_1 / I = (5.76E+14 sej/ha/yr) / (6.14E+14 sej/ha/yr) = 0.09
IR_2 $(F_1 + F_2) / I$ = (5.76 + 1.59)E+14 sej/ha/yr / (6.14E+14 sej/ha/yr) = 0.35

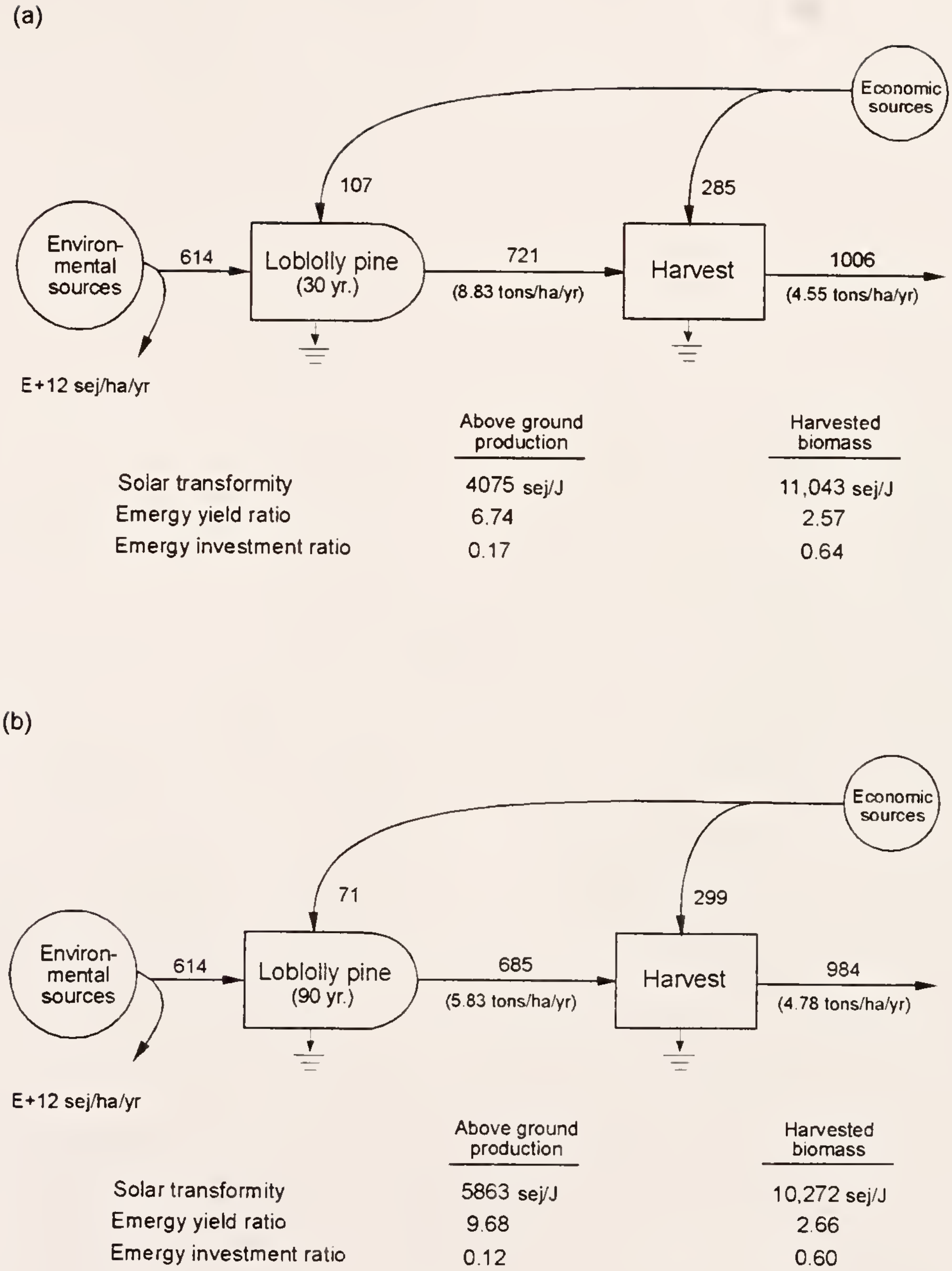
e. F_1 Items 1-6 = 5.20E+13 sej/ha/yr
F_2 Items 7-10 = 1.38E+14 sej/ha/yr
ST_1 (6.66E+14 sej/ha/yr) / (5.67E+10 J/ha/yr) = 11,740 sej/J
ST_2 (8.03E+14 sej/ha/yr) / (3.89E+10 J/ha/yr) = 20,645 sej/J
YR_1 Y_1 / F_1 = (6.66E+14 sej/ha/yr) / (5.20E+13 sej/ha/yr) = 12.81
YR_2 $Y_2 / (F_1 + F_2)$ = (8.03E+14 sej/ha/yr) / (5.20 + 1.38)E+14 sej/ha/yr = 4.24
IR_1 F_1 / I = (5.20E+14 sej/ha/yr) / (6.14E+14 sej/ha/yr) = 0.08
IR_2 $(F_1 + F_2) / I$ = (5.20 + 1.38)E+14 sej/ha/yr / (6.14E+14 sej/ha/yr) = 0.31

forest production under 60, 80 and 120 year rotation schedules. Solar transformities for loblolly pine forests (Figures 10a, 10b) were lower than for mixed hardwoods (Figures 10c, 10d, and 10e) due to higher annual above ground production rates. Transformities and emergy yield ratios for loblolly pine forests were comparable to boreal forests in southern Sweden, but mixed hardwoods had higher emergy yields and lower investment ratios.

Comparing economic emergy invested per ton harvested wood, mixed hardwood rotations invest on average 8.9E+13 sej/ton compared with 8.2E+12 sej/ton for loblolly rotations. Although the emergy yield ratios are higher for mixed hardwoods on an annual per hectare basis, loblolly pine forests require lower investments of economic emergy per unit harvested biomass. These analyses indicate that, like the boreal forests of Sweden (Figures 8 and 9), older forests with longer rotation periods deliver more net emergy than younger stands with higher investments.

Slash Pine Forests of Florida

Managed stands of slash pine in north Florida under 25 year rotation schedules were evaluated for production and harvest of pulp timber (Table 6) Measurements are summarized in Figure 11. A solar transformity for above ground production (ST_1) compared with the other conifer systems evaluated, but the transformity for harvested biomass (ST_2) measured twice that of boreal spruce/pine in Sweden or loblolly pine in Illinois. An emergy yield ratio for harvested slash pine (YR_2) was 20% lower than for 30 year old loblolly pine (Table 5). Only 37.5% of annual production in slash pine



(a)

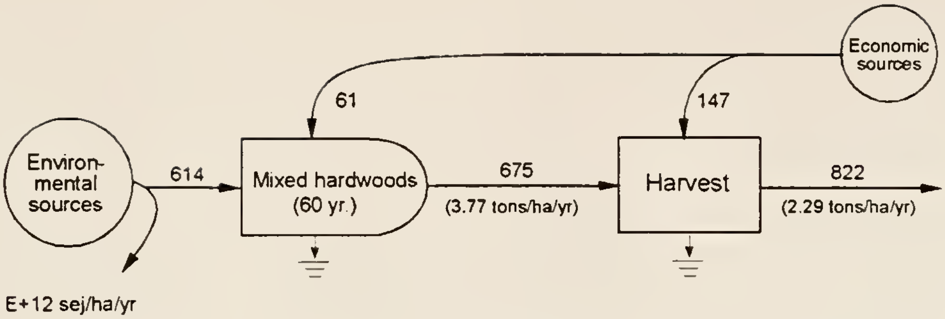
	Above ground production	Harvested biomass
Solar transformity	4075 sej/J	11,043 sej/J
Emergy yield ratio	6.74	2.57
Emergy investment ratio	0.17	0.64

(b)

	Above ground production	Harvested biomass
Solar transformity	5863 sej/J	10,272 sej/J
Emergy yield ratio	9.68	2.66
Emergy investment ratio	0.12	0.60

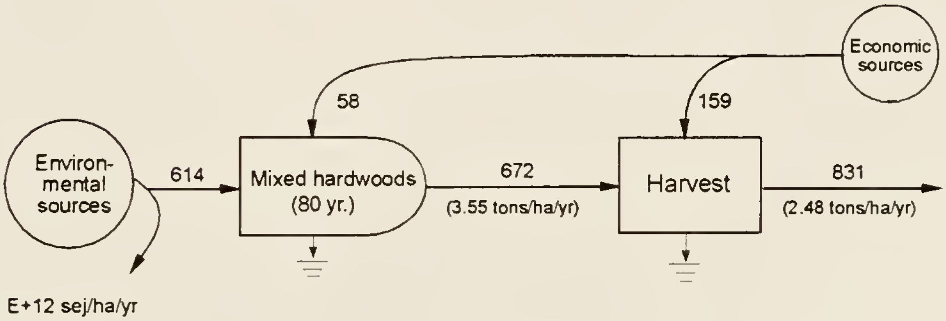
Figure 10. Systems diagrams of typical loblolly pine silvicultural production and timber extraction in the Shawnee National Forest, southern Illinois: (a) 30 year rotation schedule; (b) 90 year rotation schedule. Refer to Table 5 for calculations.

(c)



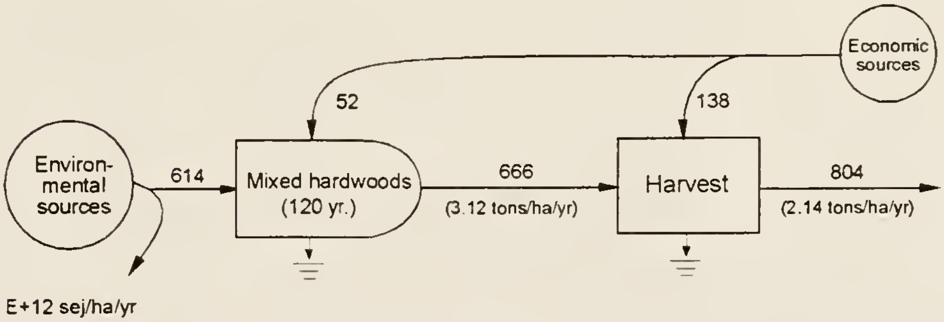
	Above ground production	Harvested biomass
Solar transformity	9834 sej/J	19,697 sej/J
Emergy yield ratio	11.03	3.95
Emergy investment ratio	0.10	0.34

(d)



	Above ground production	Harvested biomass
Solar transformity	10,399 sej/J	18,383 sej/J
Emergy yield ratio	11.65	3.84
Emergy investment ratio	0.09	0.35

(e)



	Above ground production	Harvested biomass
Solar transformity	11,740 sej/J	20,645 sej/J
Emergy yield ratio	12.81	4.24
Emergy investment ratio	0.08	0.31

Figure 10. (continued). Systems diagrams of typical mixed hardwood silvicultural production and timber extraction in the Shawnee National Forest in southern Illinois: (c) 60 year rotation schedule; (d) 80 year rotation schedule; (e) 120 year rotation schedule. Refer to Table 5 for calculations.

Table 6. Emergy evaluation of slash pine (*Pinus elliotti*) silvicultural production and timber extraction under 25 year rotation schedules in north Florida. Analysis is summarized in Figure 11.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[a]	Solar emergy flow (E+12 *sej*/ha/yr)
I	Environmental sources:			
	1. Sunlight	7.09E+13 J	1	70.9
	2. Rain, transpired	5.09E+10 J	18200	926.1
	3. Soil organic matter	1.36E+08 J	74000	10.1
F_1	Silviculture:			
	4. Phosphorus	1910 g	2.0E+10	38.2
	5. Human services	50.53 $	1.60E+12	80.9
	Y_1 Above ground production (9.6 tons/ha/yr)	1.81E+11 J	ST_1	1055.3
F_2	Harvesting:			
	6. Diesel fuel	4.45E+09 J	47900	213.0
	7. Labor	1.56E+07 J	1.09E+07	170.5
	8. Capital costs	7.90 $	1.60E+12	12.6
	Y_2 Harvested biomass (3.6 tons/ha/yr)	6.73E+10 J	ST_2	1451.4

Summary of measurements:

Solar transformity:		
ST_1	Above ground production	5829 sej/J
ST_2	Harvested biomass	21,543 sej/J
Emergy yield ratio:		
YR_1	Above ground production	8.86
YR_2	Harvested biomass	2.82
Emergy investment ratio:		
IR_1	Above ground production	0.13
IR_2	Harvested biomass	0.55

Notes.

a. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported mass use use *sej*/g; monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

Table 6--continued.

I Environmental sources:

1. Solar energy = 7092 MJ/m^2/yr (Ewel 1991) = 7.09E+13 J/ha/yr

2. Rain, chemical potential energy = 1320 mm/yr rainfall (NOAA 1982); 1030 mm/yr actual evapotranspiration (Cropper and Ewel 1983); (area) (ET) (Gibbs free energy) = (10,000 m^2/ha) (1.030 m/yr) (1000 kg/m^3) (4.94E+3 J/kg) = 5.09E+10 J/ha/yr

3. Soil used: 20 g/m^2/yr (Dissmeyer 1981); (20 g/m^2/yr) (1E+4 m^2/ha) (3% OM content) (5.4 kcal/g) (4186 J/kcal) = 1.36E J/ha/yr

F_1 Silviculture:

4. Phosphorus: 5.7 lbs/acre/yr absorbed - 4.0 lbs/acre/yr returned (Prichett 1981) = (1.7 lbs P/acre/yr) (acres/0.4047 ha) (454 g/lb) = 1910 g/ha/yr

5. Human services (Strata 1989):

	cost ($/application)	no. appl. / plantation cycle	per hectare cost ($/ha/yr)
prescribed burn:	16.10	25	16.10
tree removal (undesirables)	141.38	1	5.66
timber cruise	6.10	25	6.10
tree marking	21.19	1	0.85
site prep.	228.80	1	9.15
planting	91.11	1	3.64
thinning	137.23	1	5.49
fertilization	88.50	1	3.54
total:			50.53

Y_1 Above ground production = 461 g-C/m^2/yr (Gholtz et al. 1991); (461 g-C/m^2/yr) (1E+4 m^2/ha) (1/0.48; 48% C in OM) (4.5 kcal/g) (4186 J/kcal) = 1.81E+11 J/ha/yr

F_2 Harvesting:

6. Fuels used in harvest (Anonymous 1976): (stump to mill handling; 4 gal/ton, oven dry wt.) + (road construction and maintenance; 0.2 gal/ton) + (supervision; 0.15 gal/ton) = 4.35 gal/ton (2.86E+8 J/gal, heat content of fuel) (3.57 tons/ha/yr; harvest, Y_2 below) = 4.45E+9 J/ha/yr

7. Labor (Anonymous 1976): (harvest planning and layout; 0.06 labor-hrs/ton, oven dry wt.) + (road construction and maintenance; 0.06 hrs/ton) + (stump to mill handling; 2.21 hrs/ton) (equipment maintenance; 0.55 hrs/ton) (supervision; 0.10 hrs/ton) = 2.98 labor-hrs/ton (3.57 tons/ha/yr; harvest, item Y_2) (350 kcal/labor hr energy expenditure; Sundberg and Silversides 1988) (4186 J/kcal) = 1.56E+7 J/ha/yr

   Solar transformity for U.S. labor estimated as: (8.61E+24 sej/yr; emergy-use in U.S., 1990; Odum 1995) / (2.5E+8 people; U.S. population; (WRI 1994) / (64.5% population between ages 15-60) / (365 d/yr) / (3200 kcal/day, metabolism) / (4186 J/kcal) = 1.09E+7 sej/J.

8. Capital depreciation (Anonymous 1976): (2.21 $/ton) (3.57 ton/ha/yr; Y_2 below) = 7.90 $/ha/yr

Y_2 Harvested biomass: (73 ft^3/acre/yr; Sheffield 1981) (2.47 acres/ha) (0.028 m^3/ft^3) (0.70 ton/m^3, oven dry wt.) = 3.57 tons/ha/yr (1.88E+10 J/ton) = 6.73E+10 J/ha/yr

Table 6--continued.

Y_2 (2nd estimate): (14,983 g/m^2, tree wood biomass of 27 yr. old plantation; Gholz et al. 1986) / (27 yrs) (1E+6 g/ton) (1E+4 m^2/ha) = 5.55 tons/ha/yr (62% sawn timber, pulpwood, sawdust) = 3.45 tons/ha/yr, harvest (1.88E+10 J/ton) = 6.48E+10 J/ha/yr

Summary of measurements:

I Items 2+3 = 936.2E+12 sej/ha/yr
F_1 Items 4+5 = 119.1E+12 sej/ha/yr
F_2 Items 6+7+8 = 396.1E+12 sej/ha/yr
Y_1 $I+F_1$ = 1055.1E+12 sej/ha/yr
Y_2 $I+F_1+F_2$ = 1451.2E+12 sej/ha/yr

Solar transformities = Y_i (sej/ha/yr) / Y_i (J/ha/yr):

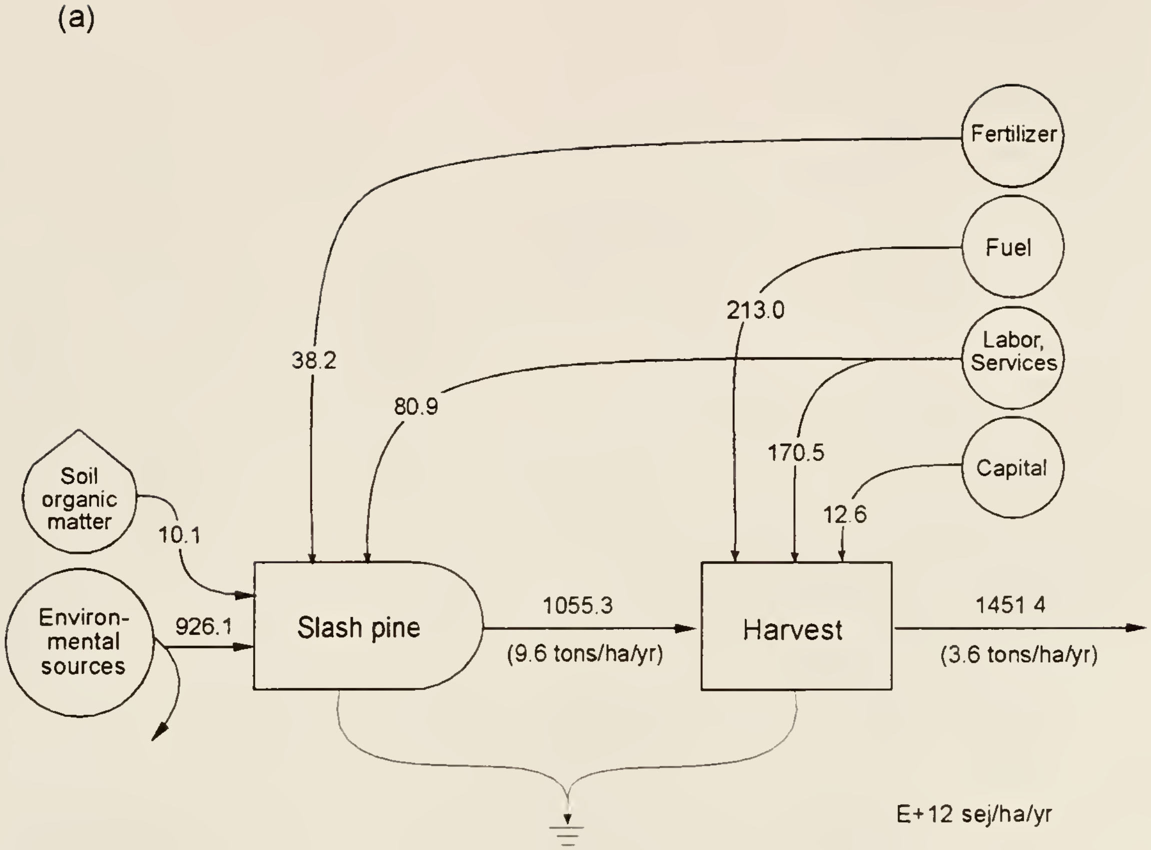
ST_1 Above ground production = (1.055E+15 sej/ha/yr) / (1.81E+11 J/ha/yr) = 5829 sej/J
ST_2 Harvested biomass = (1.451E+15 sej/ha/yr) / (6.73E+10 J/ha/yr) = 21,563 sej/J

Emergy yield ratio = Y_i / (F_1+... F_i):

YR_1 Above ground production = (1055E+12 sej/ha/yr) / (119.1E+12 sej/ha/yr) = 8.86
YR_2 Harvested biomass = (1451E+12 sej/ha/yr) / (119.1 + 396.1)E+12 sej/ha/yr = 2.82

Emergy investment ratio = (F_1+... F_i) / I:

IR_1 Above ground production = (119.1E+12 sej/ha/yr) / (936.2E+12 sej/ha/yr) = 0.13
IR_2 Harvested biomass = (119.1 + 396.1)E+12 sej/ha/yr / (936.2E+12 sej/ha/yr) = 0.55



(b)

	Above ground production	Harvested biomass
Solar transformity	5829 sej/J	21,543 sej/J
Emergy yield ratio	8.86	2.82
Emergy investment ratio	0.13	0.55

Figure 11. Systems diagram of slash pine (Pinus elliottii) silvicultural production and timber extraction under 25 year rotation schedules in north Florida: (a) solar emergy flows; (b) resource indices. Refer to Table 6 for calculations.

stands is harvested compared with 52% in loblolly and 75% in boreal spruce/pine. The emergy yield decreases 77% from production of standing crop to harvested timber, identifying the high cost of timber extraction (F_2) in southern pine stands (110.0E+12 sej/ton compared with 86.1E+12 sej/ton for 30 year old stands of loblolly pine).

Secondary Rainforests of Papua New Guinea

An emergy evaluation of a 20,000 ha lowland rainforest logging operation on the island of New Britain, Papua New Guinea is given in Table 7 and diagrammed in Figure 12. A forest-land rotation model (Doherty and Brown 1992) calculated that cleared forest land would reach a mature steady state in about 140 years with 380 tons/ha above ground biomass. A solar transformity for above ground biomass measured higher than other forest biomass evaluations, including old growth spruce/pine in Sweden and 140 year old temperate mixed hardwoods in Illinois. Emergy yield of harvested timber ($Y_2 = 2.27$) was lower than other mature forests studied and comparable with yields from younger stands due in part to a low percentage (39%) of usable timber extracted from the forest. The low yield and high investments (291.8E+12 sej/ton) is notable since there were no silviculture involved.

Emergy Evaluation of Plantation Productivity

Salix Plantations in Southern Sweden

Short-rotation willow (*Salix* spp.) cultivated on abandoned and marginal agricultural lands as fuelwood source for district heating plants in Sweden is evaluated

Table 7. Emergy evaluation of secondary tropical rainforest above ground biomass and timber extraction in New Britain, Papua New Guinea.[a] Analysis is summarized in Figure 12.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[b]	Solar emergy flow (E+15 sej/ha/yr)
I	Environmental sources:	7.77E+12 J	1.82E+04	141.41
	Q_1 Above ground biomass (380 tons/ha)	7.60E+12 J	ST_1	141.41
1.	Fuels	4.01E+10 J	5.30E+04	2.13
2.	Oil	1.00E+10 J	6.80E+04	0.68
3.	Machinery	1.66E+03 $	2.00E+12	3.32
4.	Other equipment	1.89E+02 $	2.00E+12	0.38
5.	Road construction	4.63E+08 g	1.50E+06	0.69
6.	Labor	6.75E+02 $	4.80E+13	32.41
7.	Miscellaneous costs	1.79E+03 $	2.00E+12	3.58
	Y_2 Harvested biomass (148 tons/ha/yr)	2.96E+12 J	ST_2	98.20

Summary of measurements:

Solar transformity:

ST_1	Above ground biomass	18,533	sej/J
ST_2	Harvested biomass	33,117	sej/J

Emergy yield ratio:

YR_2	Harvested biomass	2.27

Emergy investment ratio:

IR_2	Harvested biomass	0.79

Notes.

a. Data from from Tickell personal communication (1990) from an evaluation by Doherty and Brown (1992) unless cited otherwise in footnotes.

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported as mass use *sej*/g; monetary inputs use *sej*/$ for regoinal economy and year of production (Table 2 unless cited otherwise in footnotes).

Table 7--continued.

I. Environmental sources = evapo-transpired rain: (3.73 m/yr, rainfall) (60% ET) (10000 m^2) (1000 kg/m^3) (4940 J/kg) = 1.11E+11 J/ha/yr (140 years to reach mature steady state) (est. 50% used) = 7.77E+12 J/ha

Q_1 Above ground biomass: 380 tons/ha (est. Brown and Lugo 1984); (380 ton/ha) (2.0E10 J/ton) = 7.60E+12 J/ha

Y_1 Above ground production: 29.2 tons/ha/yr (est. Jordan 1971); (29.2 tons/ha/yr) (2.0E+10 J/ton) = 5.84E+11 J/ha/yr

1. Fuel used in harvest: 30,000 liters/mo; (3E+4 liters/mo) (energy content 3.60E+07 J/l) (12 mo/yr) = (1.30E+13 J/yr) / (324.3 ha/yr harvested) = 4.01E+10 J/ha/yr

2. Oil, lubricants, etc. (3500 kina/month) / (0.93 k/\$) / (0.50 \$/liter) = (7527 l/mo) (energy content, 3.60E+07 J/l) (12 mo/yr) = (3.25E+12 J/yr) / (324.3 ha/yr harvested) = 1.002E+10 J/ha/yr

3. Machinery: (capital outlay, 2.00E+6 kina) (est. lifetime, 4 yrs) / (0.93 kina/\$) = (5.38E+5 \$/yr) / (324.3 ha/yr harvested) = 1.66E+3 \$/ha/yr

4. Other equipment: (5.70E+5 kina) (est. lifetime, 10 yrs) / (0.93 kina/\$) = (6.13E+4 \$/yr) / (324.3 ha/yr harvested) = 1.89E+2 \$/ha/yr

5. Road materials: (gravel; 800 m^3/mo) (est. rock density 2.0E+6 g/m^3) (12 mo/yr) = 1.54E+11 g/yr) / (324.3 ha/yr harvested) = 4.63E+8 g/ha/yr

6. Labor: nationals, 8000 kina/mo / (0.93 kina/\$) (12 mo/yr) = 1.03E+5 \$/yr; expatriates, 9000 kina/mo / (0.93 kina/\$) (12 mo/yr) = 1.16E+5 \$/yr; total labor costs = (2.19E+5 \$/yr) / (324.3 ha/yr harvested) = 6.75E+2 \$/ha/yr

7. Miscellaneous costs = (45000 kina/mo) / (0.93 kina/\$) (12 mo/yr) = 5.81E+5 \$/yr) / (324.3 ha/yr harvested) = 1.79E+3 \$/ha/yr

Y_2 Harvested biomass: min. 120 m^3/ha, max. 250 m^3/ha; (avg. 185 m^3/ha) (0.8 tons/m^3) = 148 tons/ha (2.0E+10 J/tons) = 2.96E+12 J/ha/yr

Harvested biomass for entire operation: (1500 m^3/mo, premium quality + 3500 m^3/mo, construction quality) (0.8 tons/m^3) (12 mo/yr) = 48,000 tons/yr

Land area cut annually = (48000 tons/yr, harvested) / [(148 ton/ha, harvested) / (380 ton/ha, standing crop) = 38.9%] / (380 tons/ha, standing crop) = 324.3 ha/yr

Summary of measurements:

I_1 Environmental sources used in biomass storage (Q_1) = 141.41E+15 sej/ha

I_2 Environmental sources used in harvested biomass (Y_2) = (38.9%) (I_1) = 55.01E+15 sej/ha/yr

F_2 items 1-7 = 43.19E+15 sej/ha/yr

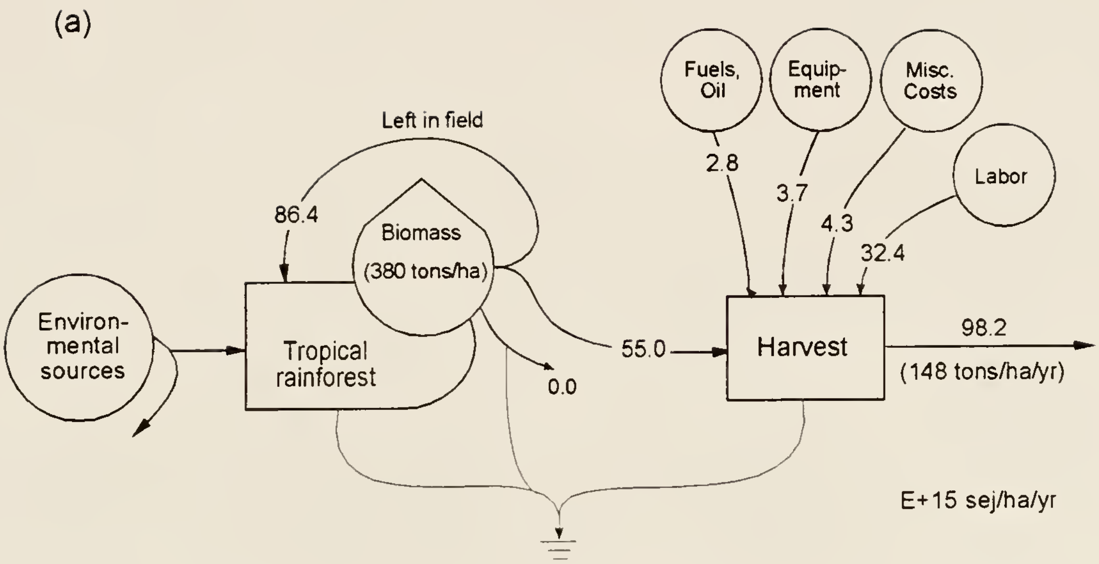
Y_2 $I_2 + F_2$ = 98.20E+15 sej/ha/yr

ST_1 Above ground biomass = (141.4E+15 sej/ha/yr) / (7.60E+12 J/ha/yr) = 18,533 sej/J

ST_2 Harvested biomass = (98.20E+15 sej/ha/yr) / (2.96E+12 J/ha/yr) = 33,117 sej/J

YR_2 Emergy yield ratio for harvested biomass = (98.20E+15 sej/ha/yr) / (43.19E+15 sej/ha/yr) = 2.27

IR_2 Investment ratio for harvested biomass = (43.19E+15 sej/ha/yr) / (55.01E+15 sej/ha/yr) = 0.79



(b)

	Above ground biomass	Harvested biomass
Solar transformity	18,533 sej/J	33,117 sej/J
Emergy yield ratio	—	2.27
Emergy investment ratio	—	0.79

Figure 12. Systems diagram of secondary tropical rainforest above ground biomass and timber extraction in New Britain, Papua New Guinea: (a) solar emergy flows; (b) resource indices. Refer to Table 7 for calculations.

in Table 8; Figure 13). Energy forestry, as it is known, is management intensive with approximately 6 harvests obtained during one planting cycle of 24 years. Every 4-5 years on average, 48 tons/ha above ground biomass is harvested, producing on average 11.5 tons/ha/yr. Plantations typically harvest a greater percentage of annual production than forests; 95% of salix biomass is removed from the field compared with 75% of biomass production in spruce/pine forests of the same region (Table 4). Cultivation emergy (F_1) measured 63.6E+12 sej/ton, almost 8 times the emergy invested in spruce/pine forests. Harvest emergy per ton harvested biomass (F_2) measured 2.3 times less than that for harvested spruce/pine, illustrating the reduction in harvest expenditures resulting in intensive high density cultivation. This is reflected in a lower transformity for harvested biomass (ST_2 = 6720 sej/J).

The emergy yield ratio for willow production (YR_1 = 1.49) was more than 8 times lower than sprue/pine. An low emergy yield ratio (YR_2 = 1.33) and high investment ratio (IR_2 = 3.02) for harvested biomass indicate very little net emergy is available as a fuel source. Irrigation is often necessary in willow plantations, though this input was not accounted for in this evaluation. A previous study of irrigated agriculture showed large investments of purchased resources from the main economy, reducing the net emergy yield (Odum et al. 1987).

Fuelwood Plantations in South Florida

Using data from Wang et al. (1981), experimental plantation production of ***Eucalyptus*** spp. and ***Melaleuca*** spp. was evaluated for use as a biomass fuel (Table 9; Figure 14). Producing 13.0 tons/ha/yr and harvested every 4.5 years, solar

Table 8. Emergy evaluation of willow (*Salix* spp.) plantation production and fuelwood harvest under 4 year rotation schedules in southern Sweden.[a] Analysis is summarized in Figure 13.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[b]	Solar emergy flow (E+12 sej/ha/yr)
I	Environmental sources:	---	---	355.1
F_1	Silviculture:			
	4. Willow cuttings[c]	6.23E+08 J	6715	4.2
	5a. Nitrogen fertilizer	7.33E+04 g	4.2E+09	307.3
	5b. Potassium fertilizer	2.46E+04 g	2.0E+09	45.2
	5c. Phosphorus fertilizer	7.90E+03 g	2.0E+10	158.4
	6. Herbicides	1.2E+07 J	66000	0.8
	7. Motor fuel	8.48E+08 J	47900	40.6
	8. Tractors	1.59E+03 g	6.7E+09	10.6
	9. Direct labor	65.97 $	1.53E+12	101.0
	10. Indirect services	41.51 $	1.53E+12	63.5
	Y_1 Above ground production (11.5 tons/ha/yr)	2.24E+11 J	ST_1	1086.7
F_2	Harvesting:			
	11. Motor fuel	2.05E+09 J	47900	98.1
	12. Tractors, trucks	1.53E+03 g	6.7E+09	10.3
	13. Human services	153.92 $	1.53E+12	236.0
	Y_2 Harvested biomass (10.9 tons/ha/yr)	2.13E+11 J	ST_2	1431.1

Summary of measurements:

Solar transformity:

ST_1	Above ground production	4850 sej/J
ST_2	Harvested biomass	6720 sej/J

Emergy yield ratio:

YR_1	Above ground production	1.49
YR_2	Harvested biomass	1.33

Emergy investment ratio:

IR_1	Above ground production	2.05
IR_2	Harvested biomass	3.02

Table 8--continued; notes.

a. Analysis based on an average willow production of 11.5 tons/ha/yr dry matter (29 m^3/ha/yr), harvested every 4-5 years and replanted with willow cuttings on a 24 year rotation (Doherty et al. 1993 using Sennerby-Forssee 1986).

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported as mass use *sej*/g; monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

c. The emergy contributions for willow cuttings were derived from the solar transformity for harvested willow (ST_2) calculated in this table. Environmental contributions (I) and societal energies (F) for cuttings were separated in spreadsheet iterations and accounted for in net yield and investment ratios to avoid double counting of inputs.

I Environmental inputs: considered the same as those for southern Sweden forests; items 1,2 and 3, Table 4, plus the environmental input to willow cuttings (item 4) used in first year planting.

F_1 Silviculture:

4. Willow cuttings = (20,000 cuttings/ha planted) / (60 cuttings/stool) (20,000 stools/harvest) / (5.75 harvests/24 yr rotation) = 0.28% of total harvested biomass; (0.28) (276 tons/ha/24 yrs) = 0.77 tons cuttings; (0.77E+6 g salix cuttings/ha) (1.95E+10 J/t) / (24 yrs/rotation) = 0.62E+9 J/ha/yr (Note: use solar transformity for harvested willow, ST_2).

5. Fertilizers:
   a. Nitrogen; 1760 kg/ha/24 yr = 7.33E+4 g/ha/yr
   b Potassium; 590 kg/ha/24yr = 2.46E+4 g/ha/yr
   c. Phoshorus; 190 kg/ha/24yr = 7.92E+3 g/ha/yr

6. Herbicides; (4 liters/ha/24 yr Roundup + 3 l/ha/24 yr Gardoprim) (9800 kcal/liter) (4186 J/kcal) = 2.87E+8 J/ha/24 yr rotation = 12E+6 J/ha/yr (Note: the heat of formation of the organic compounds in the herbicides was estimated using the heat value of petroleum, since herbicides are oil based derivatives. The caloric value of the herbicide was converted to a solar emergy estimate using a solar transformity for refined petroleum products 66,000 sej/J; Odum 1995).

7. Motor fuels: (stand establishment, 112 liters + herbicide application, 2 l + planting, 10 l + stand management, 460 l) = 572 liters/24 yrs = (23.8 l/ha/yr) (35.6E+6 J/l) = 8.5E+8 J/ha/yr

8. Tractors [(given as %wgt. (g)]: (stand establ., 10.0 hrs + hebicide appl., 0.2 + planting, 1.0 + stand mgt., 46.0)/ha/24 yr rotation = 57.2 hrs/ha/24 yr = (2.4 operating hrs/ha/yr) / (15,000 hrs useful life) (10 tons) (1E+6 g/tons)= 1.59E+3 g/ha/yr

9. Direct labor: [(stand establishment/ha/24 yr rotation; planning, 180 SEK + spraying (before planting), 94 SEK + plowing, 576 SEK + tilling, 414 SEK + planting, 7960 SEK + spraying (after planting), 94 SEK) + (stand mgt/ha/24 yr; fertilizer spreading, 258 SEK + herbicide spraying, 626 SEK + other, 90 SEK)] = 10,292 SEK/ha/24 yr rotation = (429 SEK/ha/yr) / (6.5 SEK/$US, 1988) = 65.97 $/ha/yr

10. Indirect human services: [(stand establ./ha/24 yr; herbicide, before 660 SEK + herbicide, after 318 SEK + fuel, item 7 above; (112 l) (6.5 SEK/l) = 728 SEK) + (stand mgt./ha/24 yr; fertilizer 1530 SEK + herbicide 250 SEK) + fuel, item 7 above; (460 l) (6.5 SEK/l) = 2990 SEK) = 6476 SEK/ha/24 yr = (270 SEK/ha/yr) / (6.5 SEK/US$, 1988) = 41.51 $/ha/yr

Table 8--continued.

Y_1 Willow production (annual growth) = (48 tons/harvest) (5.75 harvests/24 yr) = (276 tons/ha/24 yr) (1E+6 g/tons) (1.95E+4 J/g) / 24 yrs = 224E+9 J/ha/yr

F_2 Harvesting expenditures:

11. Motor fuel = (1380 liters/ha/rotation) (35.6E+6 J/liter) / (24 yrs/rotation) = 2.05E+9 J/ha/24 yr period

12. Tractors, trucks [(given as %wgt. (g)] = (48 tons/harvest) / (3 tons harvested/hr) (5.75 harvests/rotation) / (24 yrs/rotation) = (3.83 operating hrs/ha/yr) / (15,000 hrs useful life) (6000 kg avg. wt.) = 1.53 kg/ha/yr

13. Human services: (87 SEK/ton, havrest costs) (48 tons/harvest) / (5.75 harvests/rotation) / (24 yrs/rotation) = (30.26 SEK/ha/yr) / (6.5 SEK/$US, 1988) = 4.65 $/ha/yr

Y_2 Willow yield (calculated as production minus 5% loss) = (276 tons/ha/24 yr) (0.95) (1.95E+10 J/ton) / (24 yrs) = 213E+9 J/ha/yr

Summary of measurements:

I Item = 355.14E+12 sej/ha/yr
F_1 Items 4+... 10 = 731.6E+12 sej/ha/yr
F_2 Items 11+12+13 = 344.4E+12 sej/ha/yr
Y_1 $I+F_1$ = 1090E+12 sej/ha/yr
Y_2 $I+F_1+F_2$ = 1430E+12 sej/ha/yr

Solar transformities = Y_i (sej/ha/yr) / Y_i (J/ha/yr):

ST_1 Above ground production = (1.09E+14 sej/ha/yr) / (2.24E+11 J/ha/yr) = 4850 sej/J
ST_2 Harvested biomass = (1.43E+15 sej/ha/yr) / (2.13E+11 J/ha/yr) = 6720 sej/J

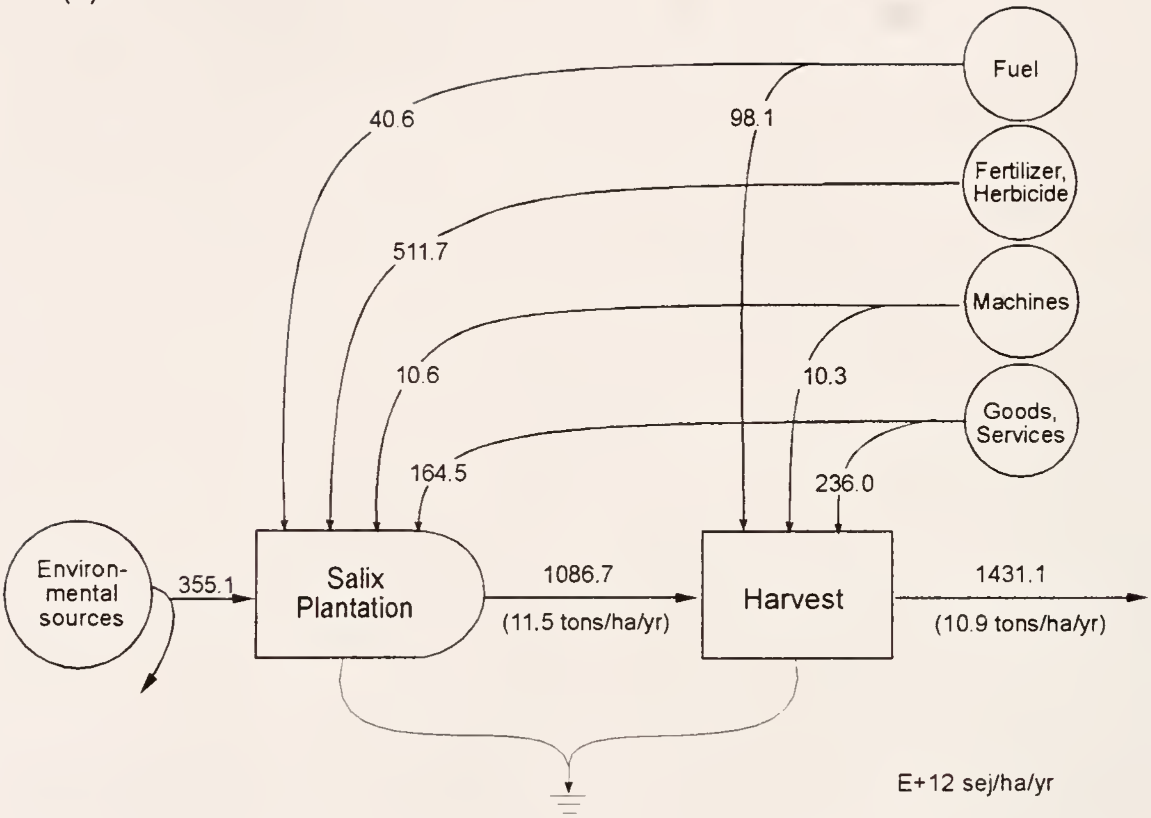
Emergy yield ratio = Y_i / (F_1+... F_i):

YR_1 Above ground production = (1090E+12 sej/ha/yr) / (731.6E+12 sej/ha/yr) = 1.49
YR_2 Harvested biomass = (1430E+12 sej/ha/yr) / (731.6 +344.4)E+12 sej/ha/yr = 1.33

Emergy investment ratio = (F_1+... F_i) / I:

IR_1 Above ground production = (731.6E+12 sej/ha/yr) / (355.1E+12 sej/ha/yr) = 2.05
IR_2 Harvested biomass = (731.16 + 344 4)E+12 sej/ha/yr / (355.1E+12 sej/ha/yr) = 3.02

(a)



(b)

	Above ground production	Harvested biomass
Solar transformity	4850 sej/J	6720 sej/J
Emergy yield ratio	1.49	1.33
Emergy investment ratio	2.05	3.02

Figure 13. Systems diagram of willow (Salix spp.) plantation production and fuelwood harvest under 4 year rotation schedules in southern Sweden: (a) solar emergy flows; (b) resource indices. Refer to Table 8 for calculations.

Table 9. Emergy evaluation fuelwood plantation production (*Eucalyptus* spp. and *Melaleuca* spp.) under 5 year rotation schedules in south Florida.[a] Analysis is summarized in Figure 14.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[b]	Solar emergy flow (E+12 sej/ha/yr)
I	Environmental sources:			
	1 Evapotranspired rain	5.09E+10 J	18200	926.3
F_1	Silviculture:			
	2 Site preparation, clearing	2.64E+09 J	47900	126.3
	3 Seedling establishment	150.00 $	3.2E+12	480.0
	4 Fertilization	1.0E+05 g	4.8E+09	480.0
	5 Irrigation	1.24E+09 J	2.55E+05	314.9
	6 Labor	1.35E+06 J	1.09E+07	14.7
	7 Human services	35.00 $	3.2E+12	112.0
	Y_1 Above ground production (13.0 tons/ha/yr)	2.18E+11 J	ST_1	2454.2
F_2	Harvesting:			
	8 Diesel fuel	5.29E+09 J	47900	253.5
	9 Human services	197.47 $	3.2E+12	631.9
	Y_2 Harvested biomass (12.4 tons/ha/yr)	2.07E+11 J	ST_2	3339.6

Summary of measurements:

Solar transformity:		
ST_1	Above ground production	11,270 sej/J
ST_2	Harvested biomass	16,143 sej/J
Emergy yield ratio:		
YR_1	Above ground production	1.61
YR_2	Harvested biomass	1.38
Emergy investment ratio:		
IR_1	Above ground production	1.65
IR_2	Harvested biomass	2.61

Notes.

a. Data compiled from Wang et al. (1981) unless cited otherwise in footnotes.

Table 9--continued

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported mass use use *sej*/g; monetary inputs use *sej*/\$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

I Environmental inputs:

1. Evapotranspired rain: (52 inches/yr, NOAA 1977) (25.4 mm/in) = (1321 mm/yr) / (1000 mm/m) (78% ET; est. using Cropper and Ewel 1983) (10,000 m^2/ha) (1000 kg/m^3) (4.94E+03 J/kg) = 5.09E+10 J/ha/yr

F_1 Silviculture inputs:

2. Site prepartion: (disking, 20.00 gal/ha + bulldozing, 12.50 gal/ha + rotovating, 10.20 gal/ha + bedding, 3.41 gal/ha) = 46.11gal/ha (2.86E+08 J/gal) = 1.32E+10 J/ha / (5 yr-rotation) = 2.64E+09 J/ha/yr
3. Seedling costs: (75 \$/1000 individuals) (1 m^2 spacing) (1E+4 m^2/ha) / (5 yrs.) = 150 \$/ha/yr
4. Fertilization: N, 50 kg/ha/yr + P, 50 kg/ha/yr = (100 kg/ha/yr) (1000 g/kg) = 1.0E+5 g/ha/yr
5. Irrigation: (0.025 m/yr) (1E+4 m^2/ha) (1000 kg/m^3) (4.94E+3 J/kg) = 1.24E+9 J/ha/yr
6. Labor: (disking, 2.43 hrs/ha + rotovating, 2.16 hrs/ha) = 4.59 hrs/ha (350 kcal/hr) (4186 J/kcal) = (6.73E+06 J/ha) / (5yrs) = 1.35E+06 J/ha/yr
7. Human services: (50 \$/ha, planting) / (5 yrs) = 10 \$/ha/yr + 25 \$/ha/yr, weeding = 35 \$/ha/yr

Y_1 Above ground production: est. 105% annual harvest [% assumed same as willow (Table 8) and eucalyptus in Thailand (Table 26)]: (12.35 tons/ha/yr, harvested; Y_2 below) (1.05) = 13.01 tons/ha/yr (4 kcal/g) (4186 J/kcal) = 2.18E+11 J/ha/yr

F_2 Harvesting inputs:

8. Fuels: (chainsaw, 33,000 Btu/ton wood + truck transport fuel, 373,000 Btu/ton) = 406,000 Btu/ton (1055 J/Btu) (12.35 ton/ha/yr harvest; Y_2 below) = 5.29E+09 J/ha/yr
9. Services: 197.47 \$/ha/yr; [mean of willow (Table 8) and eucalyptus (Table 26) costs]

Y_2 Harvested biomass: (5 tons/acre/yr) / (0.4047 ha/acre) = 12.35 ton/ha/yr (4 kcal/g) (4186 J/kcal) = 2.07E+11 J/ha/yr

Summary of measurements:

I Item 1 = 926.3E+12 sej/ha/yr
F_1 Items 2+... 7 = 1527.9E+12 sej/ha/yr
F_2 Items 8+9 = 885.4E+12 sej/ha/yr
Y_1 I+F_1 = 2454.20E+12 sej/ha/yr
Y_2 I+F_1+F_2 = 3339.6E+12 sej/ha/yr

Solar transformities = Y_i (sej/ha/yr) / Y_i (J/ha/yr):

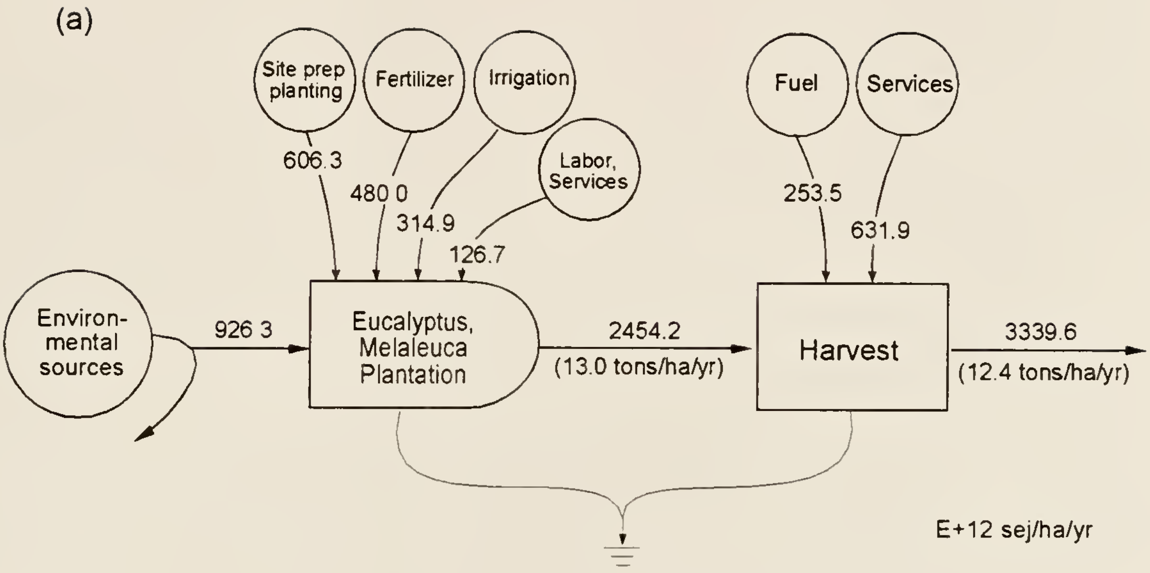
ST_1 Above ground production = (2.45E+15 sej/ha/yr) / (2.18E+11 J/ha/yr) = 11,270 sej/J
ST_2 Harvested biomass = (3.34E+15 sej/ha/yr) / (2.07E+11 J/ha/yr) = 16,143 sej/J

Emergy yield ratio = Y_i / (F_1+... F_i):

YR_1 Above ground production = (2454E+12 sej/ha/yr) / (1528E+12 sej/ha/yr) = 1.61
YR_2 Harvested biomass = (3340E+12 sej/ha/yr) / (1528 + 885)E+12 sej/ha/yr = 1.38

Emergy investment ratio = (F_1+... F_i) / I:

IR_1 Above ground production = (1528E+12 sej/ha/yr) / (926E+12 sej/ha/yr) = 1.65
IR_2 Harvested biomass = (1528 + 885)E+12 sej/ha/yr / (926E+12 sej/ha/yr) = 2.61



(b)

	Above ground production	Harvested biomass
Solar transformity	11,270 sej/J	16,143 sej/J
Emergy yield ratio	1.61	1.38
Emergy investment ratio	1.65	2.61

Figure 14. Systems diagram of plantation production and fuelwood harvest of Eucalyptus spp. and Melaleuca spp. under 5 year rotation schedules in south Florida: (a) solar emergy flows; (b) resource indices. Refer to Table 9 for calculations.

transformities were more than twice that of willow in Sweden (Table 8) but the emergy yield ratios were comparatively low. Total economic emergy investments measured 194.6E+12 sej/ton harvested fuelwood, almost twice that of willow (98.7E+12 sej/ton).

Siris Plantations of Puerto Rico

Siris (***Albizia lebbek***), a fast-growing, deciduous pioneer species, is currently being grown experimentally in Puerto Rico as a possible means of rehabilitating degraded lands (Parrotta 1992) and is used widely throughout the world as a fuelwood source. It is evaluated for production and possible harvest as a fuelwood source in Table 10 using unit investments per ton biomass from willow plantations. Figure 15 summarizes the emergy calculations. On a rotation cycle of 11 years, siris produces an average of about 10.4 tons/ha/yr above ground biomass.

Cultivation and management emergy measured 44.1E+12 sej/ton, with human services and direct manual labor accounting for over 60% of the economic sources. If harvesting only branches and stems, about 88% of annual production is removed. Total economic emergy, 82.0E+12 sej/ton, accounted for 43% of the total emergy-used. Emergy yield ratios for plantation biomass ($YR_1 = 3.15$) and harvested fuelwood ($YR_2 = 2.32$) were higher than values for other plantations. Transformities were lower for siris than for Eucalyptus and slightly higher than willow.

Table 10. Emergy evaluation of siris (*Albizia lebbek*) plantation production and possible fuelwood harvest under 11 year rotation schedules in Puerto Rico.[a] Analysis is summarized in Figure 15.

Note	Item	Resource units/ha/yr (J, g, $)		Solar emergy per unit[b]	Solar emergy flow (E+12 sej/ha/yr)
I	Environmental sources:				
	1. Rain, transpired	5.05E+10	J	18200	918.1
	2. Mineral soil	45000	g	1.12E+09	50.4
	3. Phosphorus	6800	g	2.70E+09	18.4
F_1	Silviculture:				
	4. Site preparation, planting	3.95E+08	J	47900	18.9
	5. Tractor	400	g	6.70E+09	2.7
	6. Weeding (manual labor)	1.19E+07	J	4.81E+06	57.2
	7. Seedling costs	10.85	$	1.64E+12	17.8
	8. Services	139.97	$	1.64E+12	229.6
	9. Capital expenses	81.14	$	1.64E+12	133.1
	Y_1 Above ground production (10.4 tons/ha/yr)	1.73E+11	J	ST_1	1446.8
F_2	Harvesting:				
	10. Fuels	1.63E+09	J	47900	77.9
	11. Tractor	1206	g	6.7E+09	8.1
	12. Services	122.39	$	1.64E+12	200.7
	Y_2 Harvested biomass (9.1 tons/ha/yr)	1.53E+11	J	ST_2	1733.5

Summary of measurements:

Solar transformity:			
ST_1	Above ground production	8344	sej/J
ST_2	Harvested biomass	11,335	sej/J
Emergy yield ratio:			
YR_1	Above ground production	3.15	
YR_2	Harvested biomass	2.32	
Emergy investment ratio:			
IR_1	Above ground production	0.46	
IR_2	Harvested biomass	0.76	

Table 10--continued; notes.

a. Since the siris plantation used in this evaluation was only 4.5 years old (Parrotta 1993a), rotation period was taken as the lower end of optimal rotation length for similar rain-fed plantations in India, reported as 11-14 years (Parrotta 1987a). Biomass accumulation rates are based on 4.5 years of growth.

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported mass use use *sej*/g: monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

I Environmental sources:

1. Evapotranspired rain = 1600 mm/yr (Parrotta 1992), rain; 2.8 mm/day, transpiration (64%) Bisley watershed avg. (Scatena personal communication): (2.8 mm/day) / (1000 mm/m) (365 days/yr) (1E+4 m^2/ha) (1000 kg/m^3) (4.94E+03 J/kg) = 5.05E+10 J/ha/yr

2. Mineral soil erosion = 3 mm/yr; est. (half Luquillo forest rate): (3 mm/yr) / (1000 mm/m) (1E+4 m^2/ha) (1.50E+3 g/m^3; bulk density) = 4.50E+04 g/ha/yr

3. Phosphorus (from weathering and rain): 6.80E+3 g/ha/yr; (Parrotta 1987b) ST = phosphate formation in Fla. (Odum 1995)

F_1 Silviculture (estimates using willow plantation inputs, Table 13 unless otherwise cited):

4. Fuels: (112 liters/ha; stand establ. + 10 liters/ha; planting = (122 l/ha) (3.56E+07 J/liter) = 4.34E+09 J/ha/rotation / (11.0 yr-rotation) = 3.95E+08 J/ha/yr

5. Tractors: 10 hrs/ha; stand establ. + 1 hrs/ha; planting = (11 hrs/ha) / (15000 hrs; useful lifetime) (6000 kg; tractor wt.) (1000 g/kg) = 4400 g/ha/rotation / (11.0 yr-rotation) = 400 g/ha/yr

6. Weeding (manual labor): plots were manually weeded every 2 months for 1st year (Parrotta 1993b): (0.50 hrs) / (10x10 m plot) / (2 mo.) (1.0E+4 m^2/ha) (12 mos./yr) = 300 hrs/ha/rotation (2500 kcal/day) (24 hrs/day) (4186 J/kcal) = 1.31E+08 J/ha/rotation / (11.0 yr-rotation) = 1.19E+07 J/ha/yr

7. Seedling costs: (75 $/1000 ind.; price of willow seedlings) (17500 ind./ha; avg. of 2x2m, 1x1m, 0.5x0.5m density plots (Parrotta 1993a) = 1312.5 $/ha / (11.0 yr-rotation) = 119.32 $/ha/yr / (11.0 yr-rotation) = 10.85$/ha/yr

8. Services: (122 liters fuel/ha; stand establ., planting) (0.2642 gal/l) (1.23 $/gal; U.S. avg gas price, July 1995) = 39.65 $/ha; (300 hrs/ha; manual labor, item 6) (5.00 $/hr) = 1500.00 $/ha; 1539.65 $/ha / (11.0 yr-rotation) = 139.97 $/ha/yr

9. Capital expenses: 2898 $/ha; avg. land price for areas surrounding Luquillo Experimental Forest (Scatena personal communication): (2898 $/ha) (28.00 $ / 1000 $ assessed land value; property tax) = 81.14 $/ha/yr

Y_1 Above ground production: (46.6 tons/ha above ground biomass (incl. understory) after 4.5 years (Parrotta 1993a); (46.6 tons/ha) / (4.5 yrs) = 10.36 tons/ha/yr (1.67E+10 J/ton) = (1.73E+11 J/ha/yr

Table 10--continued.

F_2 Harvest (per ton estimates using willow plantation inputs, Table 13 unless otherwise cited):

10. Fuels: (5 liter/ton) (3.56E+07 J/liter) = 1.78E+08 J/ton (9.13 tons/ha/yr; avg. harvest, Y_2 below) = 1.63E+09 J/ha/yr

11. Tractor: (0.33 hrs/ton) (15000 hrs; useful lifetime) (6000 kg; tractor wt.) (1000 g/kg) = 132 g/ton (9.13 tons/ha/yr; avg. harvest, Y_2 below) = 1206 g/ha/yr

12. Services: (13.40 $/ton) (9.13 tons/ha/yr; avg. harvest, Y_2 below) = 122.39 $/ha/yr

Y_2 Harvested biomass: 4110 g/m^2; branches, stems (w/o leaves, understory) (Parrotta 1993a); (4110 g/m^2) / (1.0E+6 g/ton) (1.0E+4 m2/ha) = 41.1 tons/ha / (4.5 yr-growth) = 9.13 tons/ha/yr (1.67E+10 J/ton) = 1.53E+11 J/ha/yr

Summary of measurements:

I Items 1+2+3 = 9.88E+14 sej/ha/yr
F_1 Items 4+... 9 = 4.59E+14 sej/ha/yr
F_2 Items 10+... 12 = 2.87E+14 sej/ha/yr
Y_1 I+F_1 = 1446.83E+12 sej/ha/yr
Y_2 I+F_1+F_2 = 1733.49E+12 sej/ha/yr

Solar transformities = Y_i (sej/ha/yr) / Y_i (J/ha/yr):

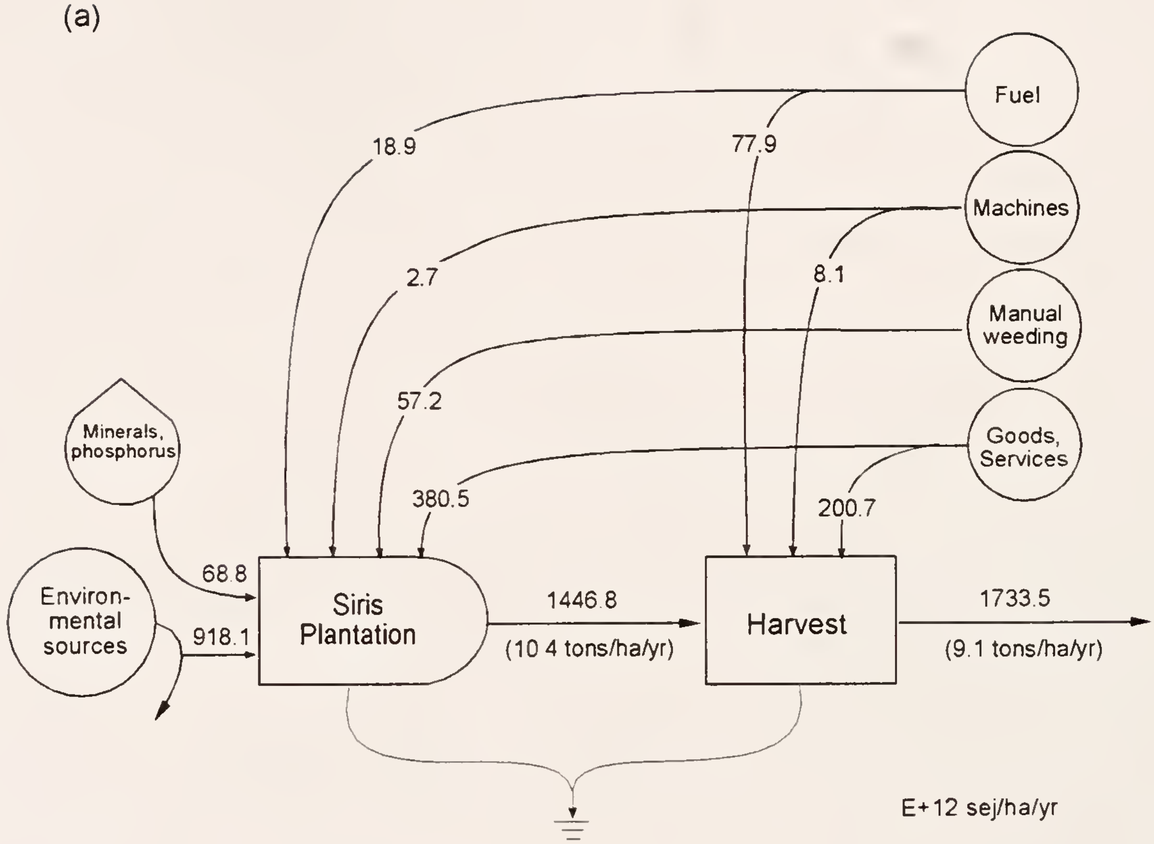
ST_1 Above ground production = (1446.83E+12 sej/ha/yr) / (1.73E+11 J/ha/yr) = 8344 sej/J
ST_2 Harvested biomass = (1733.49E+12 sej/ha/yr) / (1.53E+11 J/ha/yr) = 11,335 sej/J

Emergy yield ratio = Y_i / (F_1+... F_i):

YR_1 Above ground production = (1.45E+15 sej/ha/yr) / (4.59E+14 sej/ha/yr) = 3.15
YR_2 Harvested biomass = (1.73E+15 sej/ha/yr) / (459 + 287)E+12 sej/ha/yr = 2.32

Emergy investment ratio = (F_1+... F_i) / I:

IR_1 Above ground production = (459E+12 sej/ha/yr) / (988E+12 sej/ha/yr) = 0.46
IR_2 Harvested biomass = (459 + 287)E+12 sej/ha/yr / (988E+12 sej/ha/yr) = 0.76



(b)

	Above ground production	Harvested biomass
Solar transformity	8344 sej/J	11,335 sej/J
Emergy yield ratio	3.15	2.32
Emergy investment ratio	0.46	0.76

Figure 15. Systems diagram of siris (Albizia lebbek) plantation production and possible fuelwood harvest under 11 year rotation schedules in Puerto Rico: (a) solar emergy flows; (b) resource indices. Refer to Table 10 for calculations.

Emergy Evaluation of Non-market Forest Services

In this section, examples of ecosystem services which currently do not have identified market values are drawn from emergy evaluations of forest systems in Puerto Rico.

Carbon Sequestration

Five natural forest ecosystems in Puerto Rico were evaluated for emergy supporting annual production and stored in biomass (Table 11). These include four major forest types in the Luquillo Experimental Forest of eastern Puerto Rico: montane cloud forests, mid-elevational colorado forests, lowland tabonuco rainforests, and ubiquitous wet palm forests (Figure 16); and the Guánica tropical dry forest in southern Puerto Rico.

Montane cloud forests had the lowest annual production and a similarly low transformity (ST_1 = 2322 sej/J). Palm forests, inhabiting wet slopes and high ridges, had the highest production (Y_3 = 19.5 tons/ha/yr) but a low transformity (ST_3 = 2286) due to high surface water runoff and low plant evapo-transpiration. Lowland tabonuco rainforest had the largest production transformity (ST_4 = 9000 sej/J) and stored the greatest quantity of emergy in mature biomass (Figure 16). Dry forest biomass (Q_5 = 45 tons/ha) and cloud forest biomass represented the lowest emergy storage of Puerto Rico's forests.

Sequestration of atmospheric carbon ranged from 1.85 Mg-C/ha/yr for cloud forests to 9.75 Mg-C/ha/yr for palm forests. Tabonuco forests stored the greatest

Table 11. Emergy evaluation of above ground production and biomass storage in five natural tropical forest ecosystems in Puerto Rico. Analysis is summarized in Figure 16.

Note	Forest type	Resource units (J/ha/yr)	Solar emergy per unit[a]	Solar emergy flow (E+12 sej/ha/yr)
I_1	Montane cloud forest			
	1. Solar insolation	4.90E+13	1	49.0
	2. Wind, kinetic energy	7.90E+09	1500	11.9
	3. Rain, physical potential	3.19E+10	10500	334.9
	4. Evapotranspiration			
	a. Cloud condensation	7.90E+08	18200	14.4
	b. Direct rainfall	7.11E+09	18200	129.5
	Y_1 Net primary production	6.20E+10	ST_1	143.9
I_2	Premontane Colorado forest			
	5. Solar insolation	5.38E+13	1	53.8
	6. Wind, kinetic energy	3.95E+09	1500	5.9
	7. Rain, physical potential	4.66E+10	10500	489.3
	8. Evapo-transpired rain	4.10E+10	18200	746.2
	Y_2 Net primary production	1.27E+11	ST_2	746.2
I_3	Palm forest			
	9. Solar insolation	5.38E+13	1	53.8
	10. Wind, kinetic energy	3.95E+09	1500	5.9
	11. Rain, physical potential	4.22E+10	10500	443.0
	12. Evapo-transpired rain	4.10E+10	18200	746.2
	Y_3 Net primary production	3.19E+11	ST_3	746.2
I_4	Lowland Tabonuco forest			
	13. Solar insolation	5.84E+13	1	58.4
	14. Wind, kinetic energy	3.60E+09	1500	5.4
	15. Rain, physical potential	2.43E+10	10500	255.2
	16. Evapo-transpired rain	8.69E+10	18200	1582.4
	Y_4 Net primary production	1.76E+11	ST_4	1582.4
I_5	Guánica dry forest			
	17. Solar insolation	7.06E+13	1	70.6
	18. Evapo-transpired rain	3.57E+10	18200	649.7
	Y_5 Net primary production	1.16E+11	ST_5	649.7

Table 11--continued.

Note	Forest type	Resource units (J/ha)	Solar emergy per unit[b]	Solar emergy stored (E+15 sej/ha)
Q_1	Montane cloud forest (82.9 tons/ha)	1.38E+12	2322	3.22
Q_2	Premontane Colorado forest (135.8 tons/ha)	2.27E+12	5864	13.30
Q_3	Palm forest (199.1 tons/ha)	3.33E+12	2343	7.80
Q_4	Lowland Tabonuco forest (197.9 tons/ha)	3.31E+12	9000	29.74
Q_5	Guánica dry forest (45.0 tons/ha)	7.52E+11	5624	4.23

Notes.

a. Environmental sources are calculated as available energy and multiplied by solar transformities (*sej/J*) to obtain solar emergy.

b. Solar transformities for forest biomass are from forest production evaluations calculated as footnotes below.

I_1 Montane cloud forest:

1. Solar insolation: (3210 kcal/m^2/d) (1E+4 m^2/ha) (4186 J/kcal) (365 days/yr) = 4.9E+13 J/ha/yr

2. Wind, kinetic energy: (7.2 km/hr; Weaver et al. 1973) (1000 m/km) / (3600 sec/hr) = 5 m/s / (1000 m, vertical gradient) = 0.000025 /s^2 (1.23 kg/m^3, air density (25 m^2/sec, eddy diffusion) (31536000 sec/yr) (10,000 m^2/ha) = 2.42E+8 J/ha/yr
2nd est. using data from El Yunque (Scatena personal communication) = 7.90E+9 J/ha/yr

3. Geophysical potential energy from falling rain: [4.34 m/yr runoff, (rain = 4.5 m); Lugo 1986] (75 m, elevational change) (10,000 m^2/ha) (1000 kg/m^3) (9.8 m/s^2) = 3.19E+10 J/ha/yr

4a. Cloud condensation: [0.45 m/yr (10% of total precipitation); Weaver 1972] = 0.02 m/yr transpired (10,000 m^2/ha) (1000 kg/m^3) (4940 J/kg) = 7.9E+8 J/ha/yr

4b. Chemical potential energy of evapotranspired rain: [0.14 m/yr ET, (rain = 4.5 m + cloud condensation); Lugo 1986] (10,000 m^2/ha) (1000 kg/m^3) (4940 J/kg) = 7.11E+9 J/ha/yr

Y_1 Above ground production [NPP_{AG}] (Weaver and Murphy 1990): (3.7 tons/ha/yr) (1E+6 g/ton) (4 kcal/g; Odum 1970) (4186 J/kcal) = 6.2E+10 J/ha/yr

Q_1 Above ground biomass: (82.9 tons/ha) (1.67E+10 J/ton) = 1.38E+12 J/ha

Table 11--continued.

I_2 Premontane Colorado forest:

5. Solar insolation: (3520 kcal/m^2/d) (1E+4 m^2/ha) (4186 J/kcal) (365 d/yr) = 5.38E+13 J/ha/yr

6. Wind, kinetic energy: estimate, mean of El Yunque and Catina records = 3.95E+9 J/ha/yr (Scatena personal communication)

7. Geophysical potential energy from falling rain: [3.17 m/yr runoff, (rain = 4.0 m); Lugo 1986] (150 m, elevational change) (10000 m^2/ha) (1000 kg/m^3) (9.8 m/s^2) = 4.66E+10 J/ha/yr

8. Chemical potential energy of evapotranspired rain: (0.83 m/yr ET; Lugo 1986) (10,000 m^2/ha) (1000 kg/m^3) (4940 J/kg) = 4.10E+10 J/ha/yr

Y_2 NPP_{AG}: (7.6 tons/ha/yr) (1E+6 g/ton) (4 kcal/g) (4186 J/kcal) = 1.27E+11 J/ha/yr

Q_2 Above ground biomass: (135.8 tons/ha) (1.67E+10 J/ton) = 2.27E+12 J/ha

I_3 Palm forest:

9. Solar insolation: (3520 kcal/m^2/d) (1E+4 m^2/ha) (4186 J/kcal) (365 d/yr) = 5.38E+13 J/ha/yr

10. Wind, kinetic energy: estimate, mean of El Yunque and Catina records = 3.95E+9 J/ha/yr (Scatena personal communication)

11. Geophysical potential energy from falling rain: [2.87 m/yr runoff, (rain = 3 7 m); Lugo 1986] (150 m, elevational change) (10,000 m^2/ha) (1000 kg/m^3) (9.8 m/s^2) = 4.22E+10 J/ha/yr

12. Chemical potential energy of evapotranspired rain: (0.83 m/yr ET; Lugo 1986) (10,000 m^2/ha) (1000 kg/m^3) (4940 J/kg) = 4.10E+10 J/ha/yr

Y_3 NPP_{AG}: (19.5 tons/ha/yr) (1E+6 g/ton) (1.633E+10 J/ton) = 3.19E+11 J/ha/yr

Q_3 Above ground biomass: (199.1 tons/ha) (1.633E+10 J/ton) = 3.25E+12 J/ha

I_4 Lowland Tabonuco forest:

13. Solar insolation: (3820 kcal/m^2/d) (1E+4 m^2/ha) (4186 J/kcal) (365 d/yr) = 5.84E+13 J/ha/yr

14. Wind, kinetic energy: estimate, 3.60E+9 J/ha/yr

15. Geophysical potential energy from falling rain: [1.24 m/yr runoff, (rain = 3.0 m); Lugo 1986] (200 m, elevational change) (10,000 m^2/ha) (1000 kg/m^3) (9.8 m/s^2) = 2.43E+10 J/ha/yr

16. Chemical potential energy of evapotranspired rain: (1.76 m/yr ET; Lugo 1986) (10,000 m^2/ha) (1000 kg/m^3) (4940 J/kg) = 8.69E+10 J/ha/yr

Y_4 NPP_{AG}: (10.5 tons/ha/yr) (1E+6 g/ton) (4 kcal/g) (4186 J/kcal) = 1.76E+11 J/ha/yr

Q_4 Above ground biomass: (197.9 tons/ha) (1.67E+10 J/ton) = 3.31E+12 J/ha

Table 11--continued.

I_5 Guánica dry forest:

17. Solar insolation: 7060 MJ/m^2/yr; Lopez and Soderstrom (1983)

18. Chemical potential energy of evapotranspired rain: (0.722 m/yr ET; Lugo et al. 1978) (10,000 m^2/ha) (1000 kg/m^3) (4940 J/kg) = 3.57E+10 J/ha/yr

Y_5 NPP$_{AG}$: (6.9 tons/ha/yr; Lugo et al. 1978) (1E+6 g/ton) (4 kcal/g) (4186 J/kcal) = 1.155E+11 J/ha/yr

Q_5 Above ground biomass: (45.0 tons/ha) (1.67E+10 J/ton) = 7.52E+11 J/ha

Solar transformities for forest production, [Y_i (sej/ha/yr) / Y_i (J/ha/yr)]:

ST_1 Cloud forest = (1.44E+14 sej/ha/yr) / (6.20E+10 J/ha/yr) = 2322 sej/J
ST_2 Colorado forest = (7.46E+14 sej/ha/yr) / (1.27E+11 J/ha/yr) = 5864 sej/J
ST_3 Palm forest = (7.46E+14 sej/ha/yr) / (3.19E+11 J/ha/yr) = 2343 sej/J
ST_4 Tabonuco forest = (1.582E+15 sej/ha/yr) / (1.76E+11 sej/ha/yr) = 9000 sej/J
ST_5 Guánica dry forest = (6.50E+14 sej/ha/yr) / (1.16E+11 J/ha/yr) = 5624 sej/J

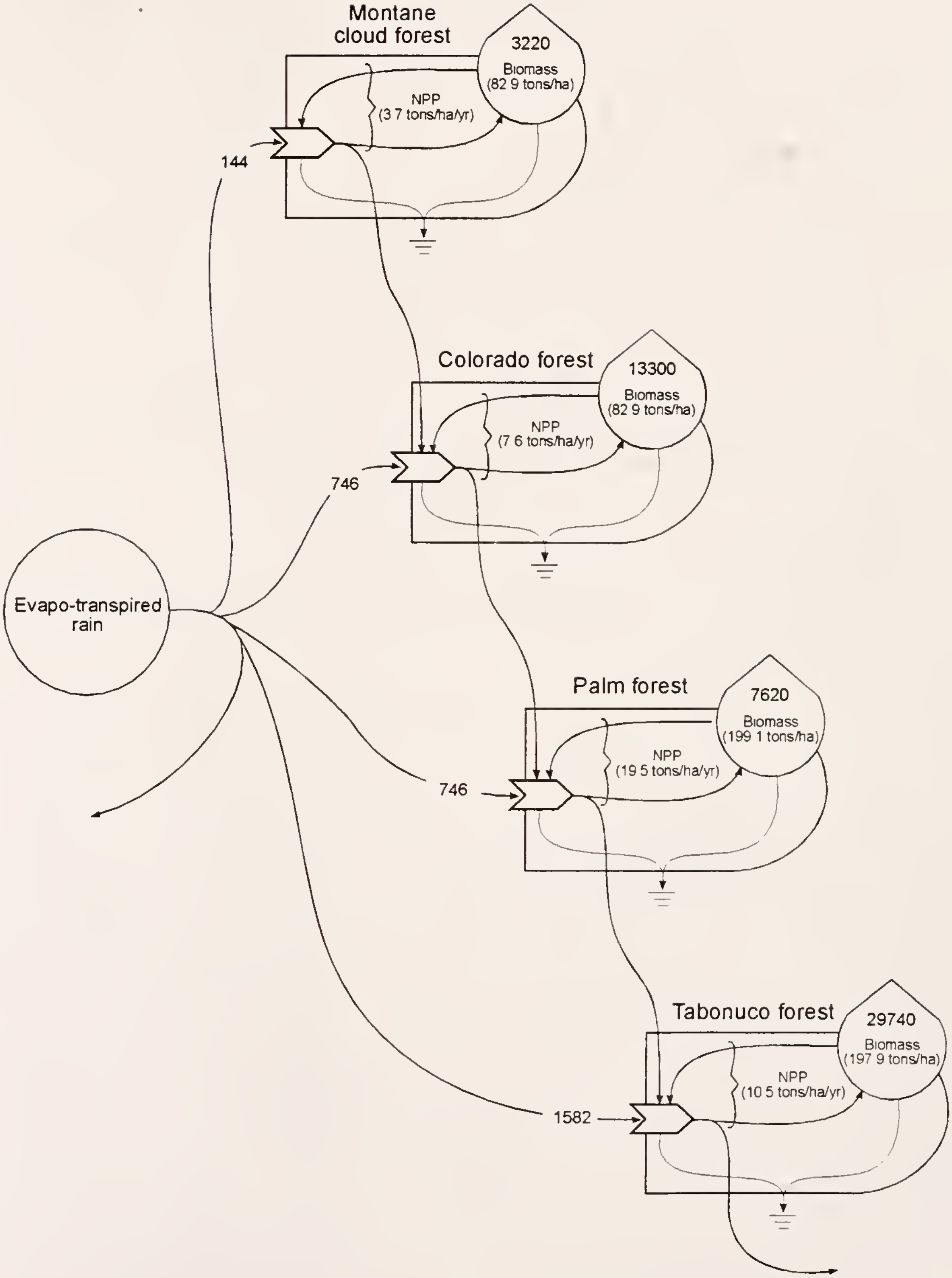


Figure 16. Systems diagram of above ground production and biomass storage in 4 natural tropical forest ecosystems of the Luquillo Experimental Forest, Puerto Rico. Pathway values are E+12 sej/ha/yr; storage values are E+12 sej/ha; values in parentheses are physical units. Refer to Table 11 for calculations.

amount of sequestered carbon (100.0 Mg-C/ha). Carbon accrual rates as a function of environmental emergy measured 77.8E+06 sej/g-C for cloud forests to 301.3E+06 sej/g-C for rainforests. Dry forests, with low seasonal rainfall supporting low forest transpiration rates, measured 188.4E+06 sej/g-C.

Reforestation

Two possible means of reforesting degraded lands in Puerto Rico were evaluated. Plantations established as foster ecosystems to direct and accelerate colonization of forest species (Table 12) were compared with unmanaged reforestation through the natural colonization of exotics and native forest species (Table 13). In the first example, the emergy used to establish a plantation of siris and the emergy of forest seeding from surrounding areas were estimated and added to the environmental emergy supporting production. In the latter case, two seed sources were evaluated along with on site environmental emergy; seeding first from exotics and then from secondary forest species after a canopy layer of exotics was established. In both cases, it was assumed that an initial forest could establish in 30 years (mean age of secondary forests in Puerto Rico) after a canopy layer of exotics was formed, either planted or through natural succession. Annual environmental source contributions from rain, eroded minerals and phosphorus (items 1,2 and 3; Tables 12 and 13) were assumed the same as those evaluated for siris plantations in the same region (Table 10). Emergy of seed sources was calculated from the area required to supply enough seeds to develop a secondary forest of 2752 mature stems/ha, estimated for both cases using known and estimated seed dispersal rates and seedling survival rates.

Table 12. Emergy evaluation of possible reforestation in Puerto Rico using a siris plantation as a foster ecosystem toward development of a secondary forest in 34 years.[a] Analysis is summarized in Figure 17a.

Note	Item	Resources units/ha (J, g, $)		Solar emergy per unit[b]	Solar emergy used in forest cycle (E+12 sej/ha/cycle)	Mean annual solar emergy flow (E+12 sej/ha/yr)
Environmental sources:						
1.	Evapotranspired rain	8.69E+11	J	18200	15,819	459.4
2.	Mineral soils	7.75E+05	g	1.12E+09	868	25.2
3.	Phosphorus	1.17E+05	g	2.70E+09	316	9.2
Seed sources:						
4.	Secondary forest seeds	---		---	788	22.9
Economic sources:						
5.	Plantation establishment	---		---	3587	104.2
6.	Capital expenses	2793.91	$	1.64E+12	4582	133.1
Forest biomass (105.6 tons/ha)		1.77E+12	J	ST_1	25,960	753.9

Summary of measurements:

Solar transformity of secondary forest biomass	14,689	sej/J
Emergy yield ratio of secondary forest biomass	3.18	
Emergy investment ratio of secondary forest biomass	0.46	

Notes.

a. Reforestation time (forest cycle) is estimated as follows: 30 years; mean age of secondary forests in Puerto Rico (Birdsey and Weaver 1982, 1987; Brown and Lugo 1990) + 4.4 yrs (required time for seeding introduction, item 4c, below) = 34.4 yrs

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported mass use use *sej*/g; monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

1. Evapotranspired rain = (5.05E+10 J/ha/yr; Table 10) (34.4 yrs. to mature forest) (50%; est. used during growth cycle) = 8.69E+11 J/ha

2. Mineral soil erosion = (4.50E+04 g/ha/yr; Table 10) (34.4 yrs. to mature forest) (50%; est. used during growth cycle) = 7.75E+05 g/ha

Table 12--continued.

3. Phosphorus = (6.80E+03 g/ha/yr; Parrotta 1987b) (34.4 yrs. to mature forest) (50%; est. used during growth cycle) = 1.17E+05 g/ha

4. Seeding from secondary forests estimated using the following:

   2752 stems/ha; 30 yr. old secondary moist forest in Puerto Rico (Birdsey and Weaver 1982, 1987)
   20%; est. no. seedlings which reach maturity (half of planted rate)
   74%; seedling survival (26% mortality rate of forest seeds under siris canopy; Parrotta 1993b)
   10%; est. seed germination
   34% dispersal success (dispersal loss = 66%)
   2.40E+03 J/seed; assume forest seeds = 2x mass of siris seeds (item 4, Table 13)
   6.00E+05 sej/J; solar transformity for forest seeds (Keitt 1991)
   3105 ind./ha/yr; mean seedling establishment rate of forest species over 6.7 years (Parrotta 1993b)

   a. Estimate of solar emergy from forest seeding: (2752 stems/ha) / (20% of seedlings reach maturity) / (74% seedlings survive) / (10% germination) / (34% dispersal success) = 5.47E+5 seeds/ha (2.40E+03 J/seed) (6.0E+05 sej/J) = 7.88E+14 sej/ha

   b. Estimate of seeds/mature stems: (5.47E+05 seeds/ha required for 2752 seeds to reach maturity) / (2752 stems/ha) = 199 seeds/stem

   c. Estimate of no. of years of seeding: (2752 stems/ha) / (20% seedlings reach maturity) / (3105 ind./ha/yr; seedling intro. rate) = 4 4 yrs. of introductions

5. Plantation establishment and management inputs = items 4+... 8, Table 10 for siris plantation.

6. Property taxes = (81.14 $/ha/yr; item 9, Table R-7) (34.4 yrs. to mature forest) = 2793.91 $/ha

Q_1 Above ground biomass: estimated for moist tropical forest type using biomass of lowland Tabonuco rainforest in proportion to differences in rainfall as follows: (197.9 tons/ha; Tabonuco biomass; item Q_4, Table 11) [(1.60 m//yr; item 1 above) / (3.0 m/yr; rain in RF; item 15, Table 11)] = 105.6 tons/ha (1.67E+10 J/ton) = 1.77E+12 J/ha

Y_1 Average annual above ground production = (105.5 tons/ha; Q_1 above) / (34.4 yrs. to mature forest) = 3.07 tons/ha/yr (1.67E+10 J/ton) = 5.13E+10 J/ha

Summary of measurements:
Environmental sources = items 1+... 3 = 17002.7E+12 sej/ha = 493.8E+12 sej/ha/yr
Seed sources = item 4 = 787.5E+12 sej/ha = 22.9E+12 sej/ha/yr
Economic sources = items 5+6 = 8169.4E+12 sej/ha = 237.5E+12 sej/ha/yr

Solar transformity of forest biomass = (25959.6E+12 sej/ha) / (1.77E+11 J/ha) = 14,689 sej/J
Emergy yield ratio of forest biomass = (25959.6E+12 sej/ha) / (8169.4E+12 sej/ha) = 3.18
Emergy investment ratio = (8169.4E+12 sej/ha) / (17002.7 + 787.5)E+12 sej/ha = 0.46

Table 13. Emergy evaluation of possible natural reforestation in Puerto Rico with initial natural seeding of exotics facilitating succession of a secondary forest in 50 years.[a] Analysis is summarized in Figure 17b.

Note	Item	Resources used in forest cycle units/ha (J, g, $)		Solar emergy per unit[b]	Solar emergy used in forest cycle (E+12 sej/ha/cycle)	Mean annual solar emergy flow (E+12 sej/ha/yr)
Environmental sources:						
1.	Evapotranspired rain	1.26E+12	J	18200	22,865	459.4
2.	Mineral soils	1.12E+06	g	1.12E+09	1254	25.2
3.	Phosphorus	1.69E+05	g	2.70E+09	457	9.2
Seed sources:						
4.	Exotic seed sources	---		---	294	5.9
5.	Secondary forest seeds	---		---	788	15.8
Economic sources:						
6.	Capital expenses	4038.45	$	1.64E+12	6623	133.1
Forest biomass (105.6 tons/ha)		1.77E+12	J	ST_1	32,281	648.6

Summary of measurements:

Solar transformity of secondary forest biomass	18,266	sej/J
Emergy yield ratio of secondary forest biomass	4.87	
Emergy investment ratio of secondary forest biomass	0.26	

Notes.

a. Reforestation time (forest cycle) is estimated as follows: 30 years (Birdsey and Weaver 1982, 1987; Brown and Lugo 1990) + 15 yrs (time required to establ. canopy layer of exotics; item 4f below) + 4.4 yrs (time required time for seeding introduction; item 4c, Table 12) = 49.8 years

b. Inputs calculated as available energy are multiplied by solar transformities (*sej/J*) to obtain solar emergy; inputs reported mass use use *sej*/g; monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

1. Evapotranspired rain = (5.05E+10 J/ha/yr; Table 10) (49.8 yrs. to mature forest) (50%; est. used during growth cycle) = 1.26E+12 J/ha

2. Mineral soil erosion = (4.50E+04 g/ha/yr; Table 10) (49.8 yrs. to mature forest) (50%; est. used during growth cycle) = 1.12E+06 g/ha

Table 13--continued.

3. Phosphorus = (6.80E+03 g/ha/yr; Parrotta 1987b) (49.8 yrs. to mature forest) (50%; est. used during growth cycle) = 1.69E+05 g/ha

4. Seeding from exotics (*Albizia* spp.) estimated as follows:

   a. Siris seed production calculated using average of two estimates:
   (2500 trees/ha; avg. stand density) (35000 seeds/tree/yr) = 8.75E+07 seeds/ha/yr;
   (12 pods/m2/day) (10 seeds/pod) (1.00E+04 m2/ha) (5 mos. production) / (12 mos/yr) (365 d/yr) = 1.83E+08 seeds/ha/yr; mean siris seed production = 1.35E+08 seeds/ha/yr

   b. Colonization rate estimate = Exotic, naturalized *Albizia procera* colonized 6.9 ha/yr from a reserve area of 114 ha (Chinea-Rivera 1992); (114 ha) / (6.9 ha/yr) = 16.5 ha/ha/yr, reserve area per unit area colonized

   c. Estimate of solar emergy from exotic seed production area: (16.5 ha/ha) (9.88E+14 sej/ha/yr; I, Table 10) = 1.63E+16 sej/ha/yr

   d. Solar transformity for exotic seeds estimated as: (1.63E+16 sej/ha/yr) / (1.35E+08 seeds/ha/yr) = 1.21E+08 sej/seed / (1200 J/seed) = 1.01E+05 sej/J

   d. No. seeds needed to produce mature canopy of exotics estimated as follows:
   (17500 stems/ha; avg. density of 3 plantation treatments used as foster ecosys.; Parrotta 1993a) / (40% of seedlings reach maturity) / [53% seedlings survive; 47% mortality (Parrotta 1993b)] / (10%; seed germination) / (34% dispersal success) = 2.43E+06 seeds/ha

   e. Solar emergy from exotic seeding: (2.43E+06 seeds/ha) (1.21E+08 sej/seed) = 2.93E+14 sej/ha

   f. Estimate of no. of years of exotic seeding: (2500 stems/ha) / (163 ind./ha/yr; seedling intro. rate; Parrotta 1993b) = 15.3 yrs. of introductions

5. Solar emergy contributed through seeding from secondary forests considered the same as that for forest succession under plantation canopy (after exotic canopy layer is formed, item 4 above): 4.4 yrs. of seed introductions using 7.88E+14 sej/ha (item 4; Table 12)

6. Property taxes = (81.14 \$/ha/yr; item 9, Table 10) (49.8 yrs. to mature forest) = 4038.45 \$/ha

Q_1 Forest biomass: same as for estimate of moist forest in Table 12; 105.6 tons/ha = 1.77E+12 J/ha

Estimate of total no. of seeds required to produce secondary forest: exotic seeds + forest seeds
= 2.43E+06 seeds/ha + 5.47E+05 seeds/ha = 2.98E+06 seeds/ha / (2752 stems/ha forest)
= 1081 seeds/mature stem

Summary of measurements:
Environmental sources = items 1+... 3 = 24576.5E+12 sej/ha = 493.8E+12 sej/ha/yr
Seed sources = items 4+5 = 1081.0E+12 sej/ha = 21.7E+12 sej/ha/yr
Economic sources = item 6 = 6623.1E+12 sej/ha = 133.1E+12 sej/ha/yr

Solar transformity for forest biomass = (32280.5E+12 sej/ha) / (1.77E+11 J/ha) = 18,266 sej/J
Emergy yield ratio for forest biomass = (32280.5E+12 sej/ha) / (6623.1E+12 sej/ha) = 4.87
Emergy investment ratio (6623.1E+12 sej/ha) / (24576.5 + 1081.0)E+12 sej/ha = 0.26

For plantation assisted reforestation, colonization of forest species begins within the first few years as a fast growing plantation canopy is developed. A dispersal of 5.5E+05 seeds/ha was considered necessary to colonize and develop a secondary forest (note 4a, Table 12) from surrounding forests or 200 seeds/mature stem (note 4b). This measured 7.88E+12 sej/ha or averaged 22.9E+12 sej/ha/yr over the development of the forest. Plantation expenses (note 5), used during the first years of plantation establishment were evaluated in Table 10 and averaged 104.2E+12 sej/ha/yr. General capital, determined from approximate property taxes (item 6) averaged 133E+12 sej/ha/yr. Environmental sources, including forest seeding accounted for 68% of the emergy required to reforest lands planted in plantations. The emergy of forest seeds, supplied for 4.4 years (note 4c) contributed 3% of the reforestation emergy. This resulted in a total of 344 years to develop a secondary forest using plantations as foster ecosystems.

In the example of reforestation through natural colonization (Table 13), the seed emergy from both exotics and forest sources was estimated. An estimated 135E+06 seeds were required to successfully colonize and develop a canopy layer of exotics (note 4a). The naturalized exotic used for reseeding was an Albizia similar to the plantation species, colonizing at a rate 6.9 ha/yr and requiring seeds from 16.5 ha/ha colonized (note 4b). Using an average environmental empower density of 9.88E+14 sej/ha/yr (Table 10), the emergy supporting seed introductions from exotic sources was estimated (note 4c) and a solar transformity for exotic seeds was calculated (note 4d) at 1.01E+5 sej/J or 1.21E+8 sej/seed; about one-sixth of the transformity for forest seeds (note 4; Table 12). A total emergy contribution from exotic seeds measured 294E+12 sej/ha (note 4e) requiring 15.3 years of introductions to establish a canopy layer (note 4f). Emergy of forest seeds colonizing under a canopy of exotics (note 5) was considered the same as the emergy of seeds colonizing under a plantation (4.4 years; Table 12). This resulted in 49.7 years to develop a secondary forest from successional organization of introduced and native species. An estimate of 1081 seeds per mature stem was required through natural reforestation, more than 5 times the seeds required using foster plantations. Environmental sources, including seeding, supplied 79% of the emergy of natural reforestation.

The two systems of reforestation are summarized and compared in Figure 17. The total emergy of reforestation, although greater for the system of natural colonization, measured on average less, reflected in a higher emergy yield ratio of 4.87 compared to 3.18 for plantation assisted reforestation. Emergy yield ratio as a function of reforestation period, was greater for the natural system of exotics and forest species (0.098/yr compared with 0.092/yr for the plantation assisted system). Both methods of reforestation indicate a positive matching of environment to economy. Plantation assisted reforestation accelerates forest seed colonization and seedling survivorship with additional emergy from economic sources. An estimated 15.3 additional years was required to reach comparable stands of secondary forest using only natural successional introductions. A difference of 1546E+12 sej/ha from economic sources measures the additional cost required to accelerate the process of reforestation, averaging 1.01E+14 sej/ha/yr of time saved.

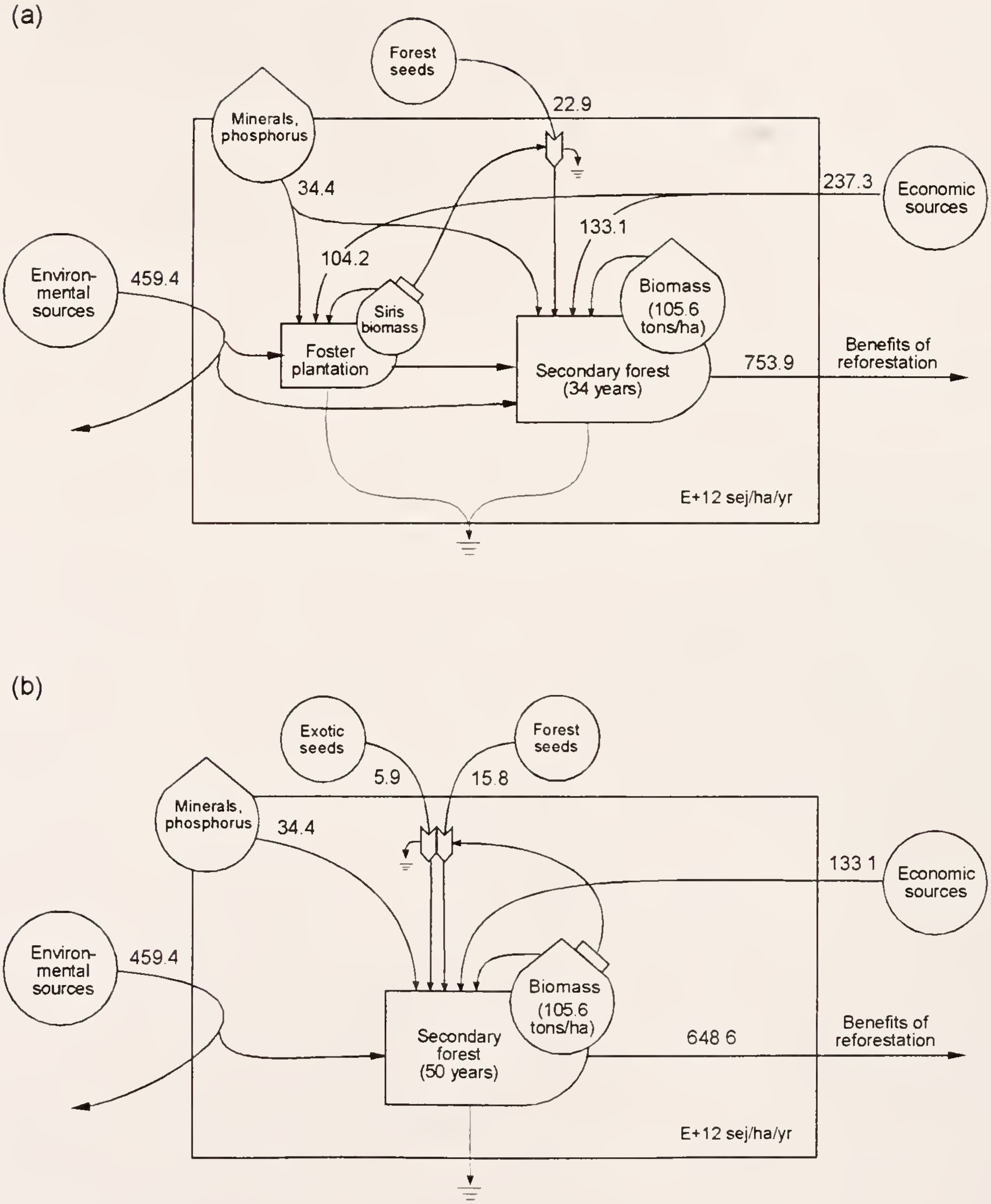


Figure 17. Systems diagrams of possible reforestation of degraded agricultural lands into secondary forests in Puerto Rico: (a) Assisted reforestation using fast growing plantation exotics as foster ecosystem; (b) natural reforestation facilitated through successional organization of exotic and forest speices from surrounding seed sources. Values are average annual flows for forest cycle. Refer to Tables 12 and 13 for calculations.

Regional Water Supply

The water budget of Luquillo Experimental Forest in Puerto Rico was evaluated for emergy flux associated with surface water runoff (Table 14). Forest watersheds provide non-market services evaluated here. Geo-potential energy of surface water runoff is used up as nutrient and sediment loads are concentrated and transported downstream, delivering water to downstream users, measured as chemical potential energy (Figure 18a). Runoff for four elevational regions, identified by forest type, ranged from 1.24 m/yr in lowland tabonuco forests (41% of incident rainfall) to 4.34 m/yr in montane cloud forests (96%).

The entire 11,268 ha forest produces 247 hm^3 of surface water runoff annually, carrying 5.64E+19 sej/yr to down stream users. Water leaving the forest carries an average 5.2E+15 sej/ha/yr in chemical potential emergy and 0.7E+15 sej/ha/yr in gravitational potential emergy. Cloud forests, with the highest runoff due to high rains and low evapo-transpiration rates, provide the greatest annual per hectare geo-potential emergy (12.85E+15 sej/ha/yr) and chemical potential emergy (6.19E+15 sej/ha/yr) of the forest elevational forest types (Figure 18b). Lowland tabonuco rainforests had the lowest per hectare runoff rate and the highest amount of emergy removed through forest evapo-transpiration.

Table 14. Annual volume runoff, energy and solar empower for surface water in four forested watersheds of the Luquillo Experimental Forest, Puerto Rico. Water cycles are summarized in Figure 18.

Note	Surface water source	Water volume (hm^3/yr)	Energy flow (J/yr)	Solar transformity[a] (sej/J)	Total emergy flow (sej/yr)	Emergy flow per hectare (E+12 sej/ha/yr)
Physical stream energy flux:						
1.	Cloud forest	18	1.71E+14	30977	5.29E+18	12850
2.	Colorado forest	104	7.65E+14	23829	1.82E+19	5550
3.	Palm forest	55	4.04E+14	23829	9.62E+18	5030
4.	Tabonuco forest	70	2.75E+14	12709	3.49E+18	620
	Total geo-potential use:	247	1.61E+15	18523	3.66E+19	
Chemical stream energy flux:						
5.	Cloud forest	18	8.80E+13	28971	2.55E+18	6190
6.	Colorado forest	104	5.12E+14	37662	1.93E+19	5870
7.	Palm forest	55	2.70E+14	37662	1.02E+19	5320
8.	Tabonuco forest	70	3.45E+14	70616	2.44E+19	4310
	Total stream discharge:	247	1.22E+15	48450	5.64E+19	

Notes.

a. Solar transformities for physical potential energy estimated using world avg. transformity (27800 sej/J; Table 2) multiplied by the proportion of mean elevation for each forest type to the average world elevation (875 m; Ryabchikov 1975):

Cloud forest: (27800 sej/J) (975 m; elevational change of forest) / (875 m) = 30977 sej/J
Colorado/palm forest: (27800 sej/J) (750 m) / (875 m) = 23829 sej/J
Tabonuco forest: (27800 sej/J) (400 m) / (875 m) = 12709 sej/J

Solar transformities for chemical potential energy of surface water flow through each forest type estimated from the global transformity (48450 sej/J; Table 2) in inverse proportion to transformities for physical stream energy calculated above:

Cloud forest: (48450 sej/J) [(18523 sej/J) / (30977 sej/J)] = 28971 sej/J
Colorado/palm forest: (48450 sej/J) [(18523 sej/J) / (23829 sej/J)] = 37662 sej/J
Tabonuco forest: (48450 sej/J) [(18523 sej/J) / (12709 sej/J)] = 70616 sej/J

Gravitational potential energy = (vol. runoff) (elevational change) (H_20 density) (gravity):

1. Cloud forest: (18E+6 m^3/yr) (975 m) (1000 kg/m^3) (9.8 m/s^2) = 1.71E+14 J/yr (30977 sej/J) = 5.29E+18 sej/yr / (412 ha) = 1.29E+16 sej/ha/yr

Table 14--continued.

2. Colorado forest: (104E+6 m^3/yr) (750 m) (1000 kg/m^3) (9.8 m/s^2) = 7.65E+14 J/yr (23829 sej/J) = 1.82E+19 sej/yr / (3285 ha) = 5.55E+15 sej/ha/yr

3. Palm forest: (55E+6 m^3/yr) (750 m) (1000 kg/m^3) (9.8 m/s^2) = 4.04E+14 J/yr (23829 sej/J) = 9.62E+18 sej/yr / (1914 ha) = 5.03E+15 sej/ha/yr

4. Tabonuco forest: (70E+6 m^3/yr) (400 m) (1000 kg/m^3) (9.8 m/s^2) = 2.75E+14 J/yr (12709 sej/J) = 3.49E+18 sej/yr / (5657 ha) = 6.2E+14 sej/ha/yr

Chemical potential stream energy = (vol. runoff) (Gibbs free energy, 4920 J/kg; typical dissolved solids for overland flow, 150 ppm) (H_2O density):

5. Cloud forest: (18E+6 m^3/yr) (4920 J/kg) (1000 kg/m^3) = 8.80E+13 J/yr (28971 sej/J) = 2.55E+18 sej/yr / (412 ha) = 6.19E+15 sej/ha/yr

6. Colorado forest: (104E+6 m^3/yr) (4920 J/kg) (1000 kg/m^3) = 5.12E+14 J/yr (37662 sej/J) = 1.93E+19 sej/yr / (3285 ha) = 5.87E+15 sej/ha/yr

7. Palm forest: (55E+6 m^3/yr) (4920 J/kg) (1000 kg/m^3) = 2.70E+14 J/yr (37662 sej/J) = 1.02E+19 sej/yr / (1914 ha) = 5.32E+15 sej/ha/yr

8. Tabonuco forest: (70E+6 m^3/yr) (4920 J/kg) (1000 kg/m^3) = 3.45E+14 J/yr (70616 sej/J) = 2.44E+19 sej/yr / (5657 ha) = 4.31E+15 sej/ha/yr

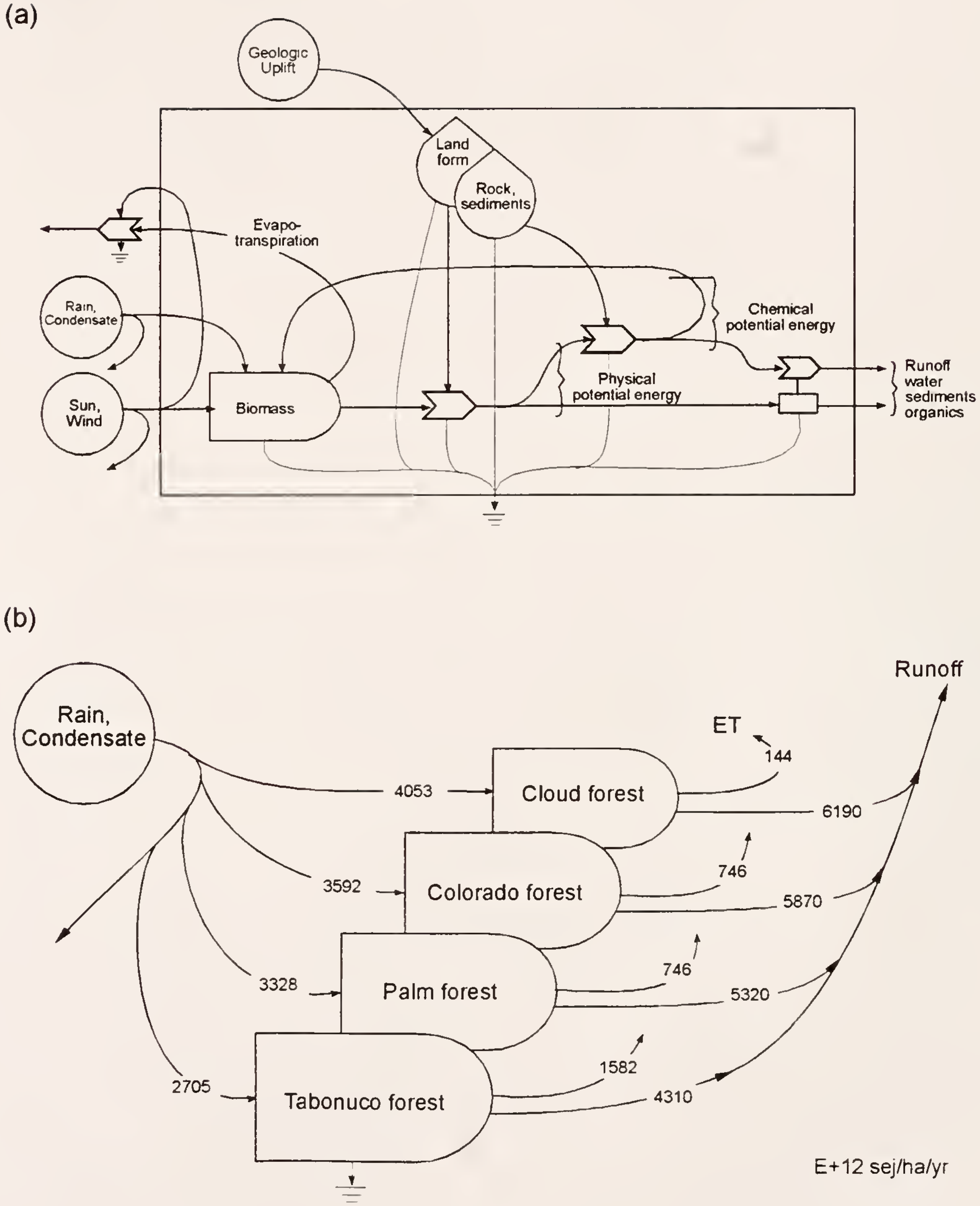


Figure 18. Systems diagrams of water cycles in forested watersheds of the Luquillo Experimental Forest, Puerto Rico: (a) overview diagram of energy flows and transformations of water using gravitational potential energy to collect surface water and concentrate chemical potential energy in runoff waters; (b) solar emergy flows of incident rainfall, forest evapotranspiration (ET) and chemical potential energy in runoff waters (refer to Table 14 for calculations).

Emergy Evaluation of Forest Economic Uses

Woodfuels

Logging residues (branches, cones and needles; 17% of average annual harvest) are being used in Sweden for development of wood fuels as an alternative to fossil fuel-fired district heating plants. Two wood fuels, wood chips and wood powder are evaluated and compared for investments, emergy yields and heat generation. Environmental emergy (I), silviculture and harvesting inputs (F_1 and F_2) were evaluated in Table 4 for spruce/pine forests. Transport costs were included in each process step.

One dry ton of wood chips produces 4197 kWh at 1473°K (Y_4, Table 15). Environmental emergy (I) accounted for 26% of the emergy supporting heat generation; wood chip production (F_3) accounted for 20%; and heating plant operations (F_4) accounted for 37% (Figure 19). Transformities increased seven fold as forest biomass was harvested, chipped and combusted. The emergy yield ratio was reduced 89% from standing crop biomass ($YR_1 = 12.39$) to district heat ($YR_4 = 1.33$). An investment ratio increased to 3.01 (IR_4) for district heat indicating that 3 times as much emergy is fedback from economic sources as is supplied from the environment. An estimate of possible mechanical work that could be derived from the high temperature heat was estimated using the Carnot cycle calculation for conversion of heat to mechanical work, assuming the slowest most efficient rate possible (ST_5 = 90,075 sej/J).

Table 15. Emergy evaluation of wood chip production and use as an alternative biomass fuel for a 10 MW district heating facility in southern Sweden.[a] Analysis is summarized in Figure 19.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[b]	Solar emergy flow (E+12 sej/ha/yr)
I	Environmental sources:	---	---	59.1
F_1	Silviculture:	---	---	5.2
F_2	Harvesting:	---	---	34.0
	Y_2 Fuelwood	9.74E+09 J	ST_2	98.3
F_3	Wood chip production:			
	Transport to roadside chipper:			
	1. Transport fuel	9.79E+07 J	47900	4.7
	2. Forwarder	172 g	6.7E+09	1.2
	3. Transport services	9.78 $	1.5E+12	14.7
	Wood chipping:			
	4. Chipper fuel	1.08E+08 J	47900	5.2
	5. Wood chipper	193 g	6.7E+09	1.3
	6. Human services	12.29 $	1.5E+12	18.5
	Y_3 Wood chips	9.25E+09 J	ST_3	143.9
F_4	Wood chip combustion:			
	Transport to heating facility:			
	7. Motor fuel	1.7E+07 J	47900	0.9
	8. Trucks	335 g	6.7E+09	2.4
	9. Transport services	5.06 $	1.5E+12	8.0
	Chip combustion			
	10. Oil	1.30E+07 J	47900	0.6
	11. Electricity	1.71E+08 J	1.25E+05	21.3
	12. Machinery	721 g	6.7E+09	4.8
	13. Human services	10.50 $	1.5E+12	15.7
	14. Capital investment	27.99 $	1.5E+12	42.0
	Y_4 High temperature heat	6.82E+09 J	ST_4	239.6
	Y_5 Mechanical output	2.66E+09 J	ST_5	239.6

Table 15--continued.

Summary of measurements:

Solar transformity:			
ST_3	Wood chips	15,557	sej/J
ST_4	High temperature heat	35,132	sej/J
ST_5	Mechanical heat	90,075	sej/J
Emergy yield ratio:			
YR_3	Wood chips	1.70	
YR_4	High temperature heat	1.33	
YR_5	Mechanical heat	1.33	
Emergy investment ratio:			
IR_3	Wood chips	1.44	
IR_4	High temperature heat	3.05	
IR_5	Mechanical heat	3.05	

Notes.

a. Analysis based on an average, sustainable production of 8.989 m^3/ha/yr (3.82 tons/ha/yr). A fuelwood harvest of 1.117 m^3/ha/yr (1/2 average volume of logging residues) is 16.7% of total harvest (6.704 m^3/ha/yr). A 5% volume loss is assumed in chipping and transport, yielding 1.061 m^3/ha/yr (Y_4) of wood chips for district heating (Doherty et al. 1993 using data from Marks 1990).

b. Inputs calculated as available energy are multiplied by solar transformities (*sej*/J) to obtain solar emergy; inputs reported as mass use *sej*/g; monetary inputs use *sej*/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

I Environmental inputs: (1.117 m^3/ha/yr) / (6.704 m^3/ha/yr harvested) = (16.7 %) (3.55E+14 sej/ha/yr; Table 4) = 59.1E+12 sej/ha/yr

F_1 Silvicultural inputs: (16.7%) (31.17E+12 sej/ha/yr; Table 4) = 5.2E+12 sej/ha/yr

F_2 Harvesting inputs: (16.7%) (203.5E+12 sej/ha/yr; Table 4) = 34.0E+12 sej/ha/yr

F_3 Wood chip production:
Transport from field to roadside chipper

1. Motor fuel = (16 liters/hr) (0.17 hrs machine operation/ha/yr; item 2) = (2.75 liters/ha/yr) (9.89 kWh/l) (3.6E+6 J/kWh) = 9.79E+7 J/ha/yr

2. Machinery depreciation [given as %wgt (g)] = [(0.15 hrs/m^3) (1.117 m^3/ha/yr)] / (12000 hrs useful lifetime) (12 ton) (1E+6 g/ton) = 172 g/ha/yr

3. Human services (total cost of production) = (56.9 SEK/m^3) (1.117 m^3 fuelwood/ha/yr harvested) = (63.56 SEK/ha/yr) / (6.5 SEK/$US, 1988) = 9.78 $/ha/yr

Table 15--continued.

Roadside chipping:

4. Oil = (30 liters/hr) (0.10 hrs. machine operation/ha/yr; note 5 calculation) (9.89 kWh/l) (3.6E+6 J/kWh) = 1.08E+8 J/ha/yr

5. Machinery depreciation [given as %wgt (g)] = [(0.093 hrs/m^3) (6.704 m^3/ha/yr) (16.7%)] / (10,000 hrs useful life) (19 tons) (1E+6 g/tons) = 193 g/ha/yr

6. Human services = (71.5 SEK/m^3) (1.117 m^3/ha/yr) / (6.50 SEK/$US, 1988) = 12.29 $/ha/yr

Y_3 Wood chips (considered 95% of annual harvest) = (.95) (1.117 m^3/ha/yr) = (1.061 m^3/ha/yr) (0.425E+6 g/m^3) (2.052E+4 J/g) = 9.25E+9 J/ha/yr

F_4 Wood chip burner:

Transport distance based on 60 km roundtrip:

7. Motor fuel = (11 kWh/ton) (3.6E+6 J/kWh) / (2.35 m^3/ton) (1.061 m^3/ha/yr) = 1.79E+7 J/ha/yr

8. Machinery depreciation [given as %wgt (g)] = [(0.093 hrs/m^3/yr) (1.061 m^3/ha/yr) / (14,000 hrs)] (50 ton) (1E+6 g/ton) = 352 g/ha/yr

9. Human services = (1.6 öre/kWh heat produced) / (100 öre/SEK) (4795 kWh heat/ton) / (2.35 m^3/ton) (1.061 m^3/ha/yr) / (6.5 SEK/$US, 1988) = 5.33 $/ha/yr

Combustion furnace:

10. Oil = (8 kWh/ton wood) / (2.35 m^3/ton) (1.061 m^3/ha/yr) (3.6E+6 J/kWh) = 1.30E+7 J/ha/yr

11. Electricity = (105 kWh/ton wood) / (2.35 m^3/ton) (1.061 m^3/ha/yr) (3.6E+6 J/kWh) = 1.71E+8 J/ha/yr

12. Machinery depreciation [given as %wgt (g)] = (0.48 hrs/ton) / (2.35 m^3/ton) = 0.20 hrs/m^3; (0.20 hrs/m^3) (1.061 m^3/ha/yr) / (30,000 hrs)] (100 ton) (1E+6 g/ton) = 721 g/ha/yr

13. Human services = (3.6 öre/kWh) / (100 SEK/öre) (4197 kWh heat/ton) = 151 SEK/ton; (151 SEK/ton) / (2.35 m^3/ton) (1.061 m^3/ha/yr) / (6.5 SEK/$US, 1988) = 10.50 $/ha/yr

14. Capital costs = (9.6 öre/kWh) / (100 SEK/öre) (4197 kWh heat/ton) = 403 SEK/ton; (403 SEK/ton) / (2.35 m^3/ton) (1.061 m^3/ha/yr) / (6.5 SEK/$US, 1988) = 27.99 $/ha/yr

Combustion of wood chips:

Y_4 High temperature heat: 1 ton of dry matter yields 4197 kWh at 1473° Kelvin = (4197 kWh heat/ton dry matter) (3.6E+6 J/kWh) = (1.51E+10 J heat/ton dry matter) (1.061 m^3 fuelwood/ha/yr) / (2.35 m^3/ton) = 6.82E+9 J heat output/ha/yr

Y_5 Mechanical heat (that fraction of total heat produced that can be used): Avg winter temp. in Sweden = 7° C, then 273° K + 7° K = 280° K; (High Temp. Heat) (Carnot Ratio) (Δ T/T) = (6.82E+9 J/ha/yr) (0.5) [(1273-280)/1273] = 2.66E+9 J/ha/yr

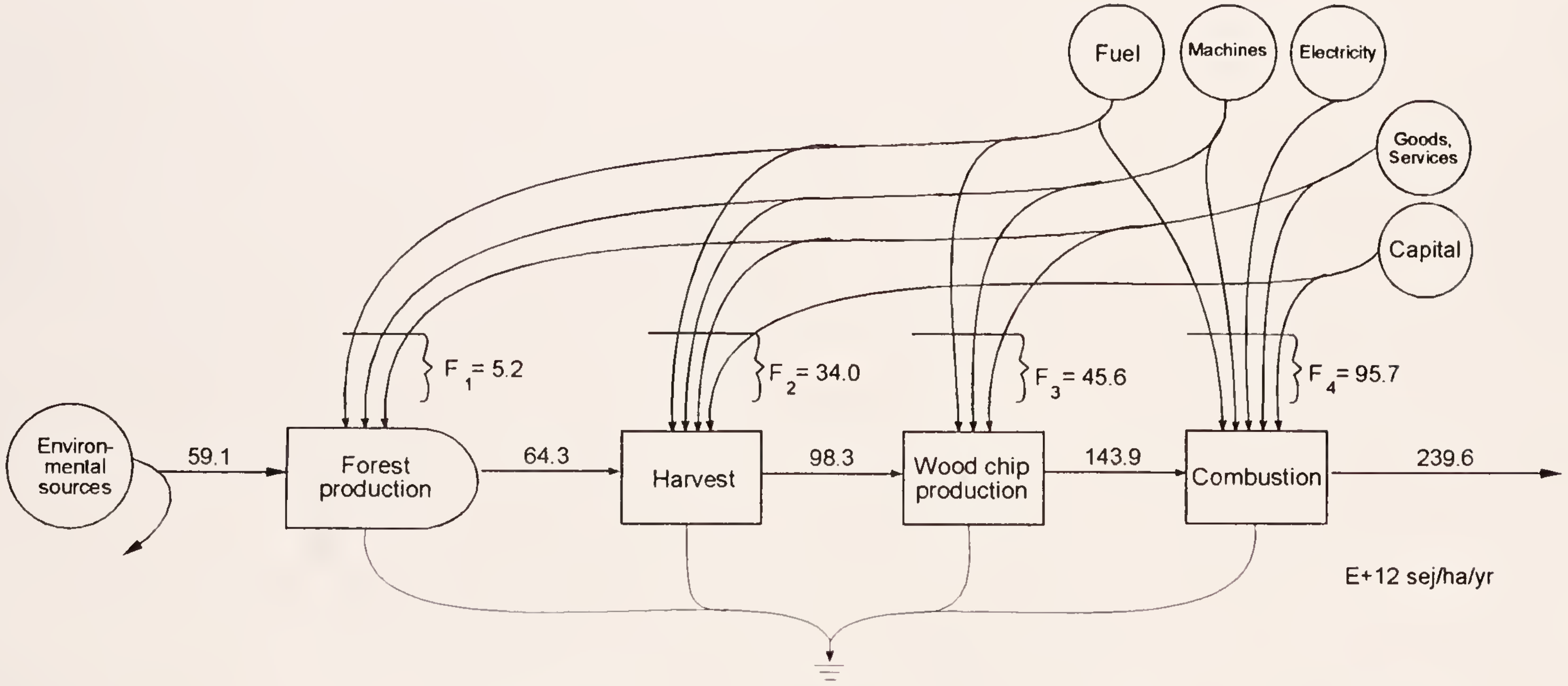
Table 15--continued.

Summary of measurements:
1 Evapo-transpired rainfall (Table 4) = 59.1E+12 sej/ha/yr
F_1 Silviculture inputs (Table 4) = 5.2E+12 sej/ha/yr
F_2 Harvesting inputs (Table 4) = 34.0E+12 sej/ha/yr
F_3 Chipping inputs; items 1+... 6 = 45.6E+12 sej/ha/yr
F_4 Wood chip combustion = 95.7E+12 sej/ha/yr
Y_2 $I+F_1+F_2$ = 98.3E+12 sej/ha/yr
Y_3 Y_2+F_3 = 143.9E+12 sej/ha/yr
Y_4 Y_3+F_4 = 239.6E+12 sej/ha/yr

Solar transformity = Y_i (sej/ha/yr) / Y_i (J/ha/yr):
ST_3 Wood chips = (144E+12 se/ha/yr) / (9.25E+9 J/ha/yr) = 15,557sej/J
ST_4 High temp. heat = (240E+12 sej/ha/yr) / (6.82E+9 J/ha/yr) = 35,132 sej/J
ST_5 Mech. heat = (240E+12 sej/ha/yr) / (2.66E+9 J/ha/yr) = 90,075 sej/J

Emergy yield ratio = Y_i / (F_1+... F_i):
YR_3 Wood chips = (144E+12 sej/ha/yr) / (5.2 + 34.0 + 45.6)E+12 sej/ha/yr = 1.70
YR_4 High temp. heat = [(240) / (5.2 + 34.0 + 45.6 + 95.7)] E+12 sej/ha/yr = 1.33
YR_5 Mechanical heat = [(240) / (5.2 + 34.0 + 45.6 + 95.7)] E+12 sej/ha/yr = 1.33

Emergy investment ratio = (F_1+... F_i) / (1):
IR_3 Wood chips = [(5.2 + 34.0 + 45.6) / (59.1)] E+12 sej/ha/yr = 1.44
IR_4 High temp. heat = [(5.2 + 34.0 + 45.6 + 95.7) / (59.1)] E+12 sej/ha/yr = 3.05
IR_5 Mechancial heat = [(5.2 + 34.0 + 45.6 + 95.7) / (59.1)] E+12 sej/ha/yr = 3.05



	Above ground production	Harvested biomass	Wood chips	District heat
Solar transformity	4928 sej/J	10,083 sej/J	15,557 sej/J	35,132 sej/J
Emergy yield ratio	12.39	2.51	1.70	1.33
Emergy investment ratio	0.09	0.66	1.44	3.05

Figure 19. Systems diagram of wood chip production and use as an alternative biomass fuel for district heating in Sweden. Refer to Table 15 for calculations.

One dry ton of wood powder produces 4795 kWh at 1473°K (Y_5, Table 16), 14.3% more heat per ton fuelwood than from wood chips. The emergy invested in wood powder production (F_4) measured the highest of purchased inputs (33% of total) with economic sources accounting for 79% of the total emergy supporting development and combustion of wood powder for heat (Figure 20). A higher transformity for heat from powder (41,243 sej/J) than from wood chips (35,132 sej/J) indicates that wood powder requires more processing (i.e., higher emergy investment ratios) and delivers less net emergy. Although wood powder burns at higher temperatures and produces more heat per dry ton of fuel than wood chips, it requires 1.3 times more investments of economic emergy per unit heat produced (3.26E+04 sej/J compared with 2.48E+04 sej/J for wood chips).

Pulp and Paper Products

Two preparations of wood pulp, chemical and mechanical, and paper products produced from harvested spruce/pine in Sweden were evaluated. All calculations are based on industry totals and averaged per ton output. Chemical methods used 4.15 m^3 of wood per ton pulp produced (Figure 21a); mechanical methods used 1.93 m^3/ton pulp (Figure 22a). Chemical pulp required 1.7E+15 solar emjoules per ton pulp (Figure 21b); mechanical methods used 4.2E+15 sej/ton (Figure 22b), resulting in solar transformities of 82,730 sej/J and 206,240 sej/J, respectively. Electricity was the largest single input to mechanical preparations. High investment ratios were calculated (6.75 for chemical pulp and 40.97 for mechanical pulp) indicating large subsidies from economic sources and the high quality of paper resources.

Table 16. Emergy evaluation of wood powder production and use as an alternative biomass fuel for a 10 MW district heating facility in southern Sweden.[a] Analysis is summarized in Figure 20.

Note	Item	Resource units/ha/yr (J, g, $)	Solar emergy per unit[b]	Solar emergy flow (E+12 sej/ha/yr)
I	Environmental sources:	---	---	64.3
F_1	Silviculture:	---	---	5.2
F_2	Harvesting:	---	---	34.0
	Y_2 Fuelwood	9.74E+09 J	ST_2	103.5
F_3	Wood chip production:	---	---	45.6
	Y_3 Wood chips	9.25E+09 J	ST_3	149.1
F_4	Wood powder production:			
	Transport to powder plant:			
	1. Motor fuel	1.8E+07 J	47900	1.0
	2. Trucks	352 g	6.7E+09	2.4
	3. Transport services	4.96 $	1.5E+12	7.4
	Powder production:			
	4. Wood powder[c]	7.32E+08 J	29200	16.2
	5. Oil	1.3E+07 J	47900	0.6
	6. Electricity	3.12E+08 J	1.25E+05	38.9
	7. Machines	30 g	6.7E+09	0.2
	8. Human services	15.84 $	1.5E+12	23.8
	9. Capital investment	6.67 $	1.5E+12	10.0
	Y_4 Wood powder	8.35E+09 J	ST_4	249.6
F_5	Wood powder combustion:			
	10. Transport to heating facility	---	---	10.7
	11. Electricity	9.88E+07 J	1.25E+05	12.3
	12. Machinery	685 g	6.7E+09	4.6
	13. Human services	8.23 $	1.5E+12	12.3
	14. Capital investment	10.76 $	1.5E+12	16.1
	Y_5 High temperature heat	7.4E+09 J	ST_5	305.6
	Y_6 Mechanical output	3.0E+09 J	ST_6	305.6

Table 16--continued.

Summary of measurements:

Solar transformity:

ST_4	Wood powder	29,892	sej/J
ST_5	High temperature heat	41,297	sej/J
ST_6	Mechanical heat	101,870	sej/J

Emergy yield ratio:

YR_4	Wood powder	1.35
YR_5	High temperature heat	1.27
YR_6	Mechanical heat	1.27

Emergy investment ratio:

IR_4	Wood powder	2.88
IR_5	High temperature heat	3.75
IR_6	Mechanical heat	3.75

Notes.

a. Analysis based on an average, sustainable production of 8.989 m^3/ha/yr (3.82 tons/ha/yr). A fuelwood harvest of 1.117 m^3/ha/yr (1/2 average volume of logging residues) is 16.7% of annual harvest (6.704 m^3/ha/yr). A 5% volume loss is assumed in chipping and transport (Y_4 = 1.061 m^3/ha/yr) and an additional 5% loss during production and delivery of wood powder to district plant yields 1.008 m^3/ha/yr (Y_5) for combustion (Doherty et al. 1993).

b. Inputs calculated as available energy are multiplied by solar transformities (***sej***/J) to obtain solar emergy; inputs reported as mass use ***sej***/g, monetary inputs use ***sej***/\$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes).

c. The emergy contribution for wood powder (item 4) as an internal fuel for drying was derived from the solar transformity calculated in this table. Environmental contributions and societal energies for wood powder were separated in spreadsheet iterations and accounted for in emergy yield and investment ratios to avoid double counting as follows:

I_{powder} = (1 - 1/YR_4) (item 4; 21.4E+12 sej/ha/yr) = 5.2E+12 sej/ha/yr;
F_{powder} = (21.4 - 5.2)E+12 sej/ha/yr = 16.2E+12 sej/ha/yr.

I Environmental inputs: (1.117 m^3/ha/yr fuelwood) / (6.704 m^3/ha/yr harvested) = (16.7%) (355.1E+12 sej/ha/yr; Table 4) = 59.1E+12 sej/ha/yr + 5.2E+12 sej/ha/yr (I_{powder}) = 64.2E+12 sej/ha/yr

F_1 Silvicultural inputs: (16.7%) (31.17E+12 sej/ha/yr; Table 4) = 5.20E+12 sej/ha/yr

F_2 Harvesting inputs to fuelwood. (16.7%) (203.5E+12 sej/ha/yr; Table 4) = 3.4E+13 sej/ha/yr

Y_2. Fuelwood harvest, wood still in the field (1 117 m^3/ha/yr of wood = 16.7% of average annual harvest); (16.7%) (8.989 m^3/ha/yr) (0.425E+6 g/m^3) (2.052E+4 J/g) = 9.74E+09 J/ha/yr

Table 16--continued.

F_3 Wood chipping 45.6E+12 sej/ha/yr (Table 15)

F_4 Wood powder production:

Transport of wood chips from roadside to wood powder plant (60km avg. roundtrip distance).

1. Motor fuel = (11 kWh/ton wood) (3.6E+6 J/kWh) / (2.35 m^3/ton) (1.061 m^3/ha/yr) = 1.79E+7 J/ha/yr

2. Machinery depreciation [given as %wgt (g)] = (0.093 hrs/m^3) (1.061 m^3/ha/yr) / (14000 hrs)*(50 ton, truck and trailor) (1E+6 g/ton) = 352 g/ha/yr

3. Human services = maintenence + labor costs; maint. costs = 11.80 SEK/m^3 and labor costs = (0.093 driving hrs/m^3) (200 SEK/hr) = 18.6 SEK/m^3; 11.80 + 18.6 = 30.4 SEK/m^3 (1.061 m^3/ha/yr) / (6.5 SEK/$US,1988)= 4.96 $/ha/yr

Powder production:

4. Wood powder fuel (for drying); 0.08 m^3 wood for powder per 1 m^3 wood processed into powder; (450 kWh/ton) / (2.35 m^3/ton) (1.061 m^3/ha/yr) (3.6E+6 J/kWh) = 7.32E+8 J/ha/yr

5. Oil = (8 kWh/ton) (3.6E+6 J/kWh) / (2.35 m^3/ton) (1.061 m^3/ha/yr) = 1.3E+7 J/ha/yr

6. Electricity consumption = (192 kWh/ton) (3.6E+6 J/kWh) / (2.35 m^3/ton) (1.061 m^3/ha/yr) = 3.12E+8 J/ha/yr

7. Machinery depreciation [given as %wgt (g)] = (6500 hr/yr) / (100,000 ton powder/yr processed) / (2.35 m^3/ton) (1.061 m^3/ha/yr) = [(0.03hrs/ha/yr) / (6500 hr/yr) (15 yrs)] (100 ton) (1E+6 g/ton) = 30 g/ha/yr

8. Human services = (228 SEK/ton) / (2.35 m^3/ton) = 9.7 SEK/m^3 (1.061 m^3/ha/yr) / (6.50 SEK/$US, 1988) = 15.84 $/ha/yr

9. Capital investment = (9.6 SEK/ton powder prod.) / (2.35 m^3/ton) = 4.09 SEK/m^3; (4.09 SEK/m^3) (1.061 m^3/ha/yr) / (6.5 SEK/$US, 1988) = 6.67 $/ha/yr

Y_4 Wood powder (considered 95% of volume of wood chips): (.95) (1.061 m^3/ha/yr) = (1.008 m^3/ha/yr) (0.425E+6 g/m^3) (2.052E+4J/g) = 8.35E+09 J/ha/yr

F_5 Wood powder combustion:

10. Transport distance (60 km roundtrip) and delivery costs of wood powder is considered the same as transport of wood chips (60 km roundtrip distance; Table R-15).

11. Electricity consumption = (64 kWh/ton) (3.6E+6 J/kWh) / (2.35 m^3/ton) (1.008 m^3 fuelwood/ha/yr) = 9.88E+7 J/ha/yr

12. Machinery depreciation [given as %wgt (g)] = (0.48 hrs/ton) / (2.35 m^3/ton) = 0.20 hrs/m^3 (1.008 m^3/ha/yr) / (30,000 hrs. useful life) (100 ton) (1E+6 g/ton) = 685 g/ha/yr

13. Human services = (2.6 öre/kWh heat produced) / (100 öre/SEK) (4795 kWh heat/ton) = 125 SEK/ton / (2.35 m^3/ton) (1.008 m^3/ha/yr) / (6.5 SEK/$US, 1988) = 8.23 $/ha/yr

14. Capital costs = (3.4 öre/kWh heat produced) / (100 öre/SEK) (4795 kWh heat/ton) = 163 SEK/ton / (2.35 m^3/ton) (1.008 m^3/ha/yr) / (6.50 SEK/$US, 1988) = 10.76 $/ha/yr

Table 16--continued.

Wood powder combustion:

Y_5 High temperature heat: 1 ton of dry matter yields 4795 kWh at 1473° Kelvin = (4795 kWh heat/ton) (3.6E+6 J/kWh) = (1.73E+10 J heat/ton dry matter) (1.008 m^3/ha/yr) / (2.35 m^3/ton) = 7.4E+9 J heat output/ha/yr

Y_6 Mechanical heat (that fraction of total heat produced that can be used mechanically): Avg winter temp. in Sweden = 7° C, then 273° K + 7° K = 280° K; Mechanical heat = (High Temp. Heat) (Carnot Ratio) (Δ T/T) = (7.4E+9 J/ha/yr) (0.5) [(1473-280) / 1473)] = 3.0E+9 J/ha/yr

Summary of measurements:

I 59.1E+12 sej/ha/yr + (item 4; environmental component of wood powder[c], 5.2E+12 sej/ha/yr) = 64.3E+12 sej/ha/yr
F_4 Items 1+... 9 = 100.5E+12 sej/ha/yr
F_5 Items 10+... 14 = 56.0E+12 sej/ha/yr
Y_4 $I+F_1+\ldots F_4$ = 249.6E+12 sej/ha/yr
Y_5 $Y_4+F_1+\ldots F_5$ = 305.6E+12 sej/ha/yr

Solar transformity = Y_i (sej/ha/yr) / Y_i (J/ha/yr):

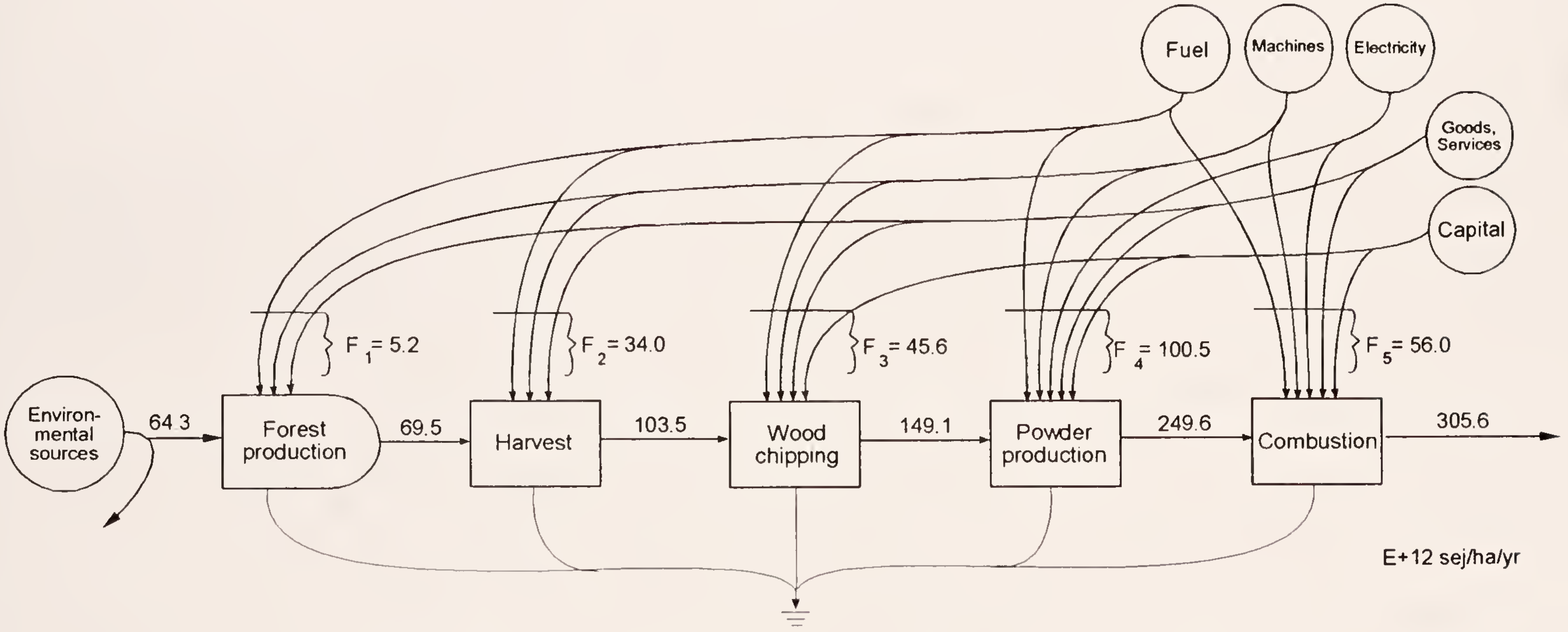
ST_4 Wood powder = (249E+12 sej/ha/yr) / (8.35E+9 J/ha/yr) = 29,892 sej/J
ST_5 High temp. heat = (305E+12 sej/ha/yr) / (7.40E+9 J/ha/yr) = 41,297 sej/J
ST_6 Mechancial heat = (305E+12 sej/ha/yr) / (3.00E+9 J/ha/yr) = 101,870 sej/J

Emergy yield ratio = Y_i / ($F_1+\ldots F_i$):

YR_4 Wood powder = (249.6E+12 sej/ha/yr) / (5.2 + 34.0 + 45.6 + 100.5)E+12 sej/ha/yr = 1.35
YR_5 District heat = [(305.6) / (5.2 + 34.0 + 45.6 + 100.5 + 55.9)] E+12 sej/ha/yr = 1.27

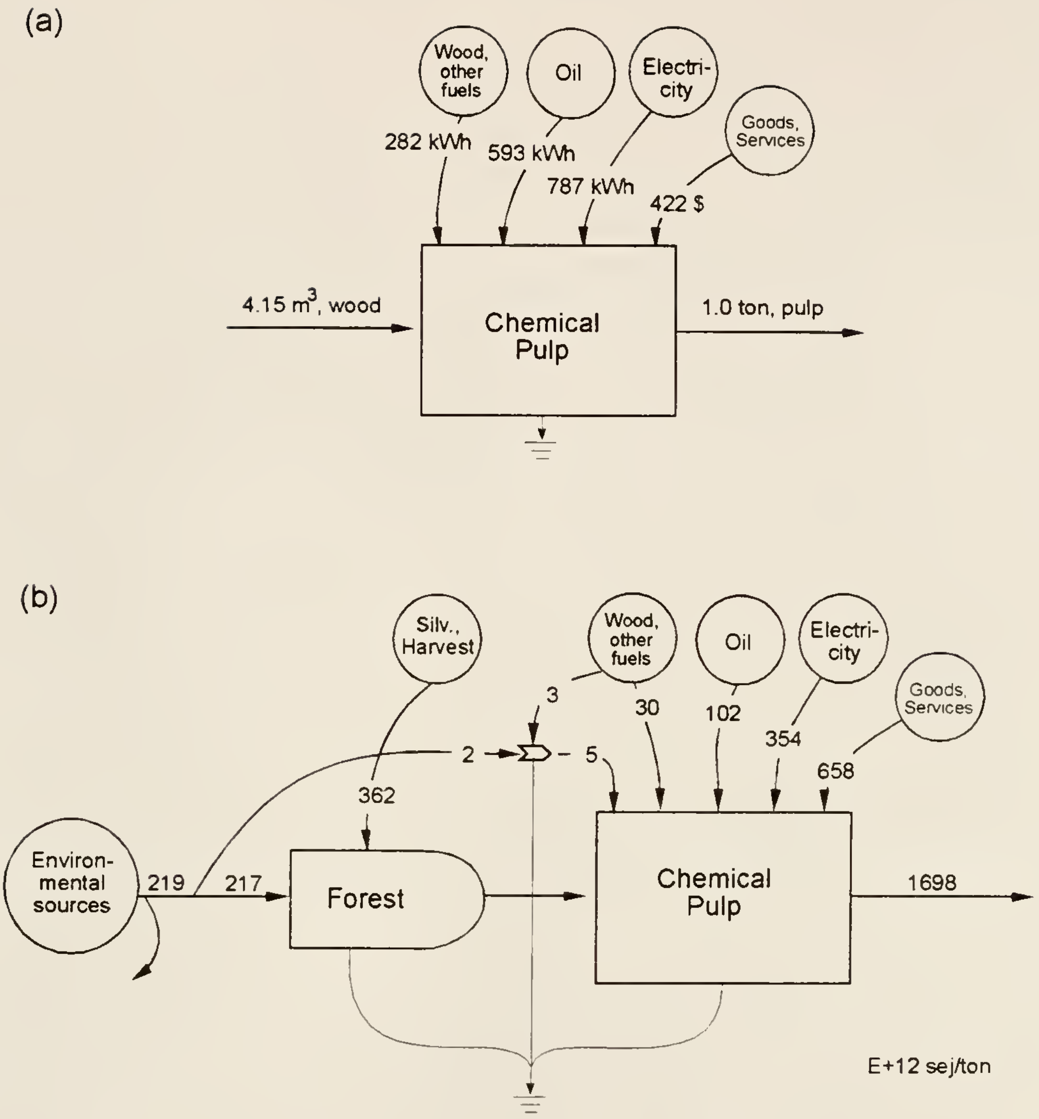
Emergy investment ratio = ($F_1+\ldots F_i$) / (I):

IR_4 Wood powder = (5.2 + 34.0 + 45.6 + 100.5)E+12 sej/ha/yr / (64.3E+12 sej/ha/yr) = 2.88
IR_5 District heat = [(5.2 + 34.0 + 45.6 + 100.5 + 55.9) / (64.3)] E+12 sej/ha/yr = 3.75



	Above ground production	Harvested biomass	Wood chips	Wood powder	District heat
Solar transformity	4928 sej/J	10,083 sej/J	15,557 sej/J	29,892 sej/J	41,292 sej/J
Emergy yield ratio	12.39	2.51	1.70	1.35	1.27
Emergy investment ratio	0.09	0.66	1.44	2.88	3.75

Figure 20. Systems diagram of wood powder production and use as an alternative biomass fuel for district heating in Sweden. Refer to Table 16 for calculations.



(c)

Solar transformity	82,730 sej/J
Emergy yield ratio	1.15
Emergy investment ratio	6.75

Figure 21. Systems diagram of chemical production of 1 ton of wood pulp: (a) physical units; (b) solar emergy; (c) resource indices. Calculations given as footnotes.

Figure 21--continued; notes.

Calculations are based on one ton of wood pulp production using chemical treatment in Sweden, 1988 (sulfate and sulfite methods are combined here for overview) (data from Skogsstyrelsen 1989).

Estimate of wood volume input (m^3/ton pulp) based on industry totals: 13.49E+6 m^3, forest wood + 3.89E+6 m^3, industry byproducts = 17.38E+6 m^3 / (4.19E+6 ton chem. pulp prod.) = 4.15 m^3/ton

F_1 Wood input: (4.15 m^3 wood / ton chem. pulp) (0.425 ton/m^3) (2.052E+10 J/ton) = 36.2E+9 J/ton (16000 sej/J; ST for wood chips, Table 15) = 579E+12 sej/ton ch. pulp;
where emergy yield ratio for transported wood chips = 1.7 (Table 15), then
F_1 = (1 / 1.7) (579E+12 sej/ton) = 362E+12 sej/ton
I_1 = [(1.7 - 1.0) / (1.7) (579E+12 sej/ton) = 217E+12 sej/ton

F_2 Wood fuels: (0.3E+9 kWh/yr) / (4.188E+6 ton/yr, ch. pulp) = (71.6 kWh/ton) (3.6E+6 J/kWh) = 0.26E+9 J/ton (16000 sej/J; ST for wood chips, Table 15) = 4.2E+12 sej/ton;
where emergy yield ratio for transported wood chips = 1.7 (Table 15), then
F_2 = (1 / 1.7) (4.2E+12 sej/ton) = 2.6E+12 sej/ton
I_2 = [(1.7 - 1.0) / (1.7) (4.2E+12 sej/ton) = 1.6E+12 sej/ton

F_3 Other, intermediate fuels: [(.94) (0.3E+9 kWh/yr) + 0.6E+9 kWh/yr] / (4.188E+6 ton, ch. pulp) = (210.5 kWh/ton) (3.6E+6 J/kWh) = 0.76E+9 J/ton (4E+4 sej/J; intermediate ST for coal) = 30.3 E+12 sej/ton

F_4 Oil: [(.94) (0.3E+9 kWh/yr) + 2.2E+9 kWh/yr] / (4.188E+6 ton/yr, ch. pulp) = (592.6 kWh/ton) (3.6E+6 J/kWh) = 2.13E+9 J/ton (47900 sej/J) = 102E12 sej/ton

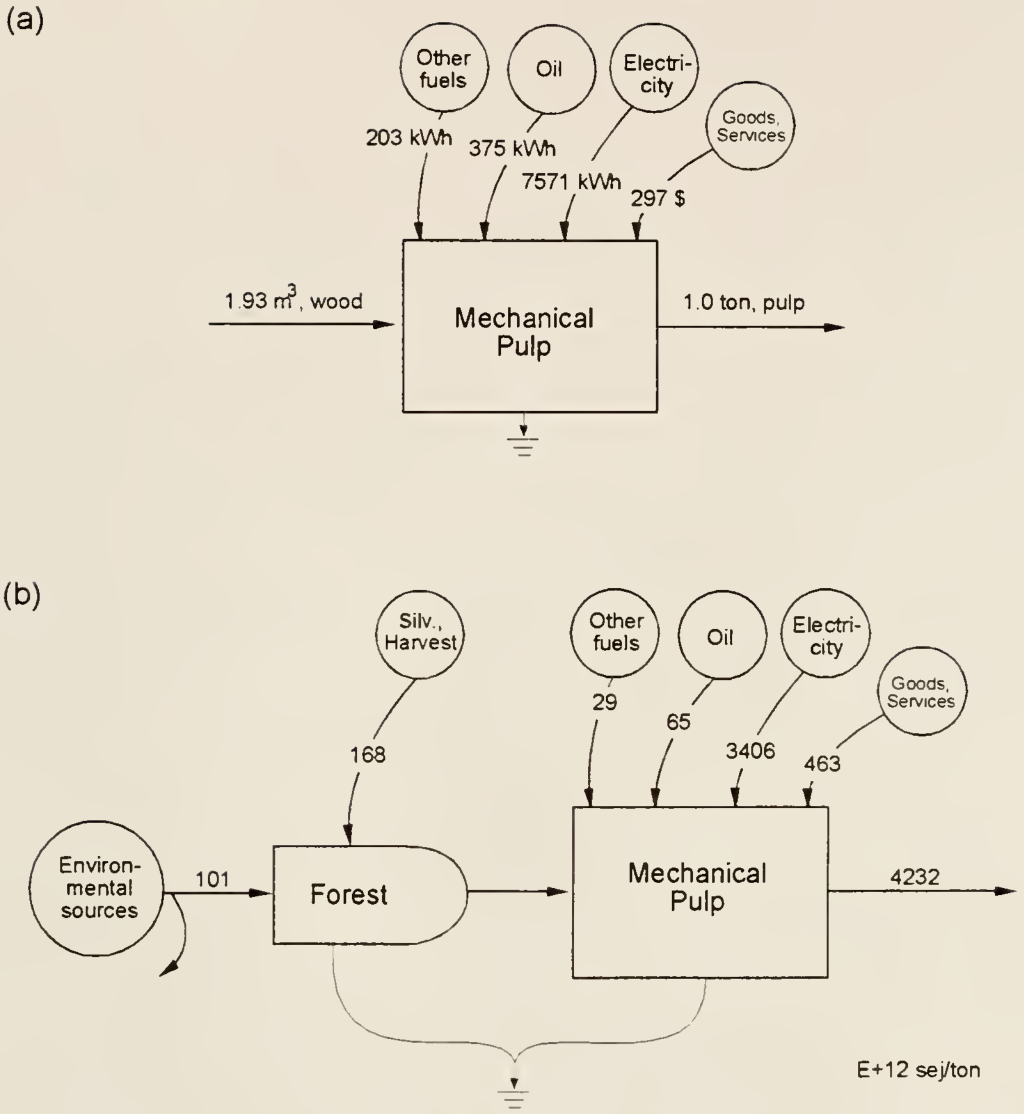
F_5 Electricity: [(.94) (0.1E+9 kWh/yr) + 3.2E+9 kWh/yr] / (4.188E+6 ton/yr, ch. pulp) = (786.5 kWh/ton) (3.6E+6 J/kWh) = 2.83E+9 J/ton (1.25E+5 sej/J) = 354E+12 sej/ton

F_6 Production costs: estimated as export value less 10%; (sulfate, 2989 SEK/ton) (86.5% tot. ch. pulp) + (sulfite, 3415 SEK/ton) (13.5% tot. ch. pulp) = (3045 SEK/ton) / (6.5 SEK/$, 1988) (0.90) = 421 $/ton (1.5E+12 sej/$) = 658E+12 sej/ton

Summary of measurements:

I $I_1 + I_2$ = (217 + 1.6)E+12 sej/ton = 219E+12 sej/ton
F F_1+... F_6 = 1479E+12 sej/ton
Y I + F = 1698E+12 sej/ton

ST (1698E+12 sej/ton) / (2.052E+10 J/ton) = 82,730 sej/J
YR (1698E+12 sej/ton) / (1479E+12 sej/ton)= 1.15
IR (1479E+12 sej/ton) / (219E+12 sej/ton) = 6.75



(c)

Solar transformity	206,240 sej/J
Emergy yield ratio	1.03
Emergy investment ratio	40.97

Figure 22. Systems diagram of mechanical production of 1 ton of wood pulp: (a) physical units; (b) solar emergy; (c) resource indices. Calculations given as footnotes.

Figure 22--continued; notes.

Calculations are based on one ton of wood pulp production using mechanical, crushing methods in Sweden, 1988 (data from Skogsstyrelsen 1989):

Estimate of wood volume input (m^3/ton pulp) based on industry totals: 0.88E+6 m^3, forest wood + 0.25E+6 m^3, industry byproducts = 1.13E+6 m^3 / (0.58E+6 ton mech. pulp prod.) = 1.93 m^3/ton

F_1 Wood input: (1.93 m^3 wood / ton mech. pulp) (0.425 ton/m^3) (2.052E+10 J/ton) = 16.3E+9 J/ton (16000 sej/J; ST for wood chips, Table 15) = 269E+12 sej/ton mech. pulp; where emergy yield ratio for wood chips = 1.7 (Table 15), then
F_1 = (1 / 1.7) (269E+12 sej/ton) = 168E+12 sej/ton
I_1 = [(1.7 - 1.0) / (1.7) (269E+12 sej/ton) = 101E+12 sej/ton

F_2 Other fuels: [(.06) (0.3E+9 kWh/yr) + 0.1E+9 kWh/yr] / (0.582E+6 ton/yr, mech. pulp) = (203.3 kWh/ton) (3.6E+6 J/kWh) = 0.732E+9 J/ton (4E+4 sej/J; intermediate ST for coal) = 29.3E+12 sej/ton

F_3 Oil: [(.06) (0.3E+9 kWh/yr) + 0.2E+9 kWh/yr] / (0.582E+6 ton/yr, mech. pulp) = (375.1 kWh/ton) (3.6E+6 J/kWh) = 1.35E+9 J/ton (47900 sej/J) = 64.7E+12 sej/ton

F_4 Electricity: [(.06) (0.1E+9 kWh/yr) + 4.4E+9 kWh/yr] / (0.582E+6 ton/yr, mech. pulp) = (7571 kWh/ton) (3.6E+6 J/kWh) = 27.3E+9 J/ton (1.25E+5 sej/J) = 3406E+12 sej/ton

F_5 Production costs: estimated as export value less 10%; (2142 SEK/ton) / (6.5 SEK/4) (0.90) = 297 \$/ton (1.5E+12 sej/\$) = 463E+12 sej/ton

Summary of measurements:

I I_1 = 101E+12 sej/ton
F F_1+... F_6 = 4131E+12 sej/ton
Y I + F = 4232E+12 sej/ton

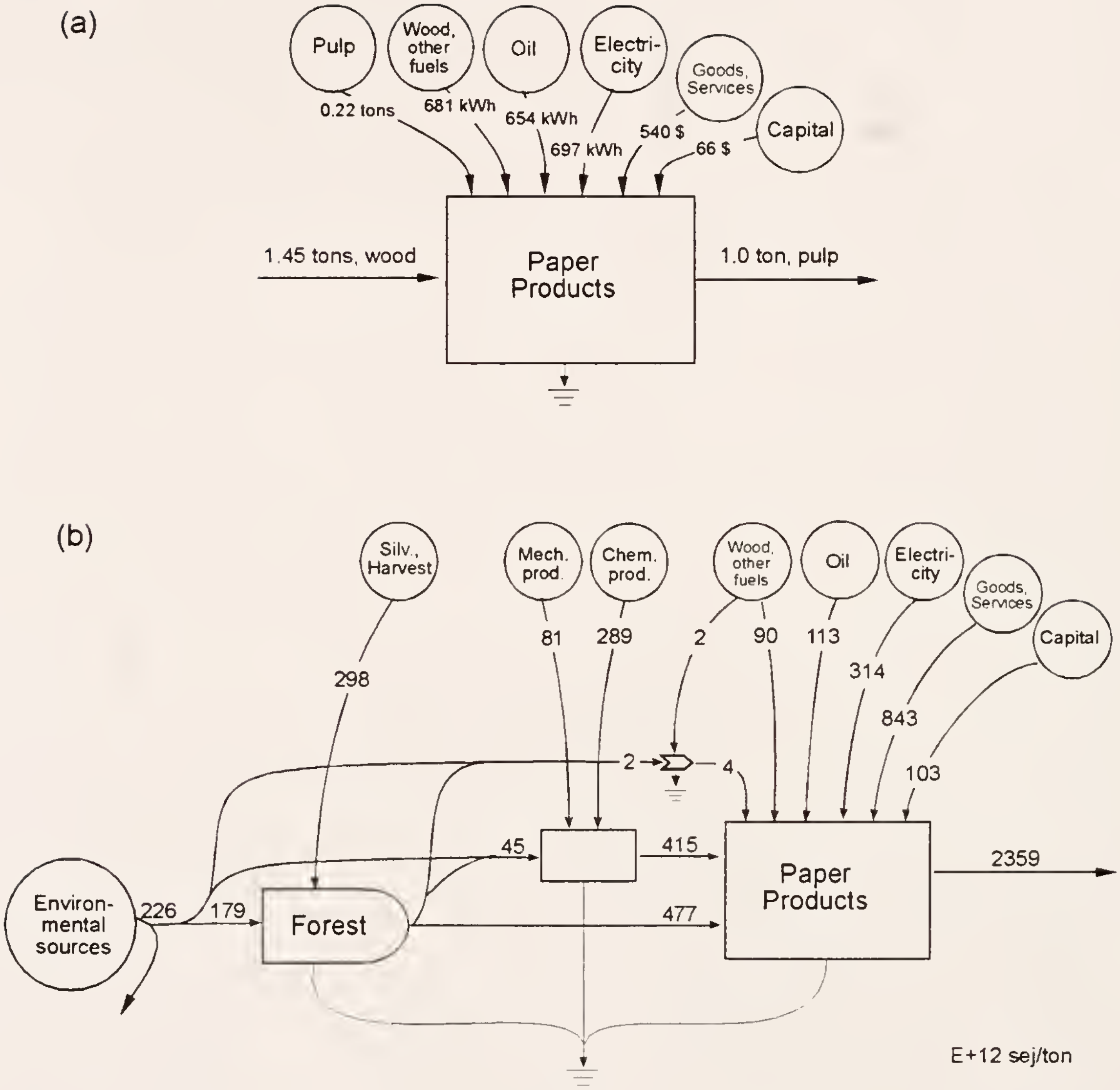
ST 4232E+12 sej/ton / (2.052E+10 J/ton) = 206,240 sej/J
YR (4232E+12 sej/ton) / (4131E+12 sej/ton) = 1.03
IR (4131E+12 sej/ton) / (101E+12 sej/ton) = 14.90

Paper products, including newspaper, writing paper and cardboard, were combined for an evaluation of Sweden's paper industry. Using national production data, an average of 3.42 m^3 of wood resources were used per ton of paper products (Figure 23a). A solar transformity of 114,960 sej/J and an emergy investment ratio of 10.44 were measured for paper products (Figure 23b).

Tourism and Recreation

An analysis of the emergy supporting tourism in the Luquillo Experimental Forest in Puerto Rico, was undertaken to evaluate the role of the forest in providing recreational opportunities and the net benefit delivered to the economy (Table 17). Environmental contributions (I) were calculated in Tables 11 and 14 and summed for the entire Luquillo Experimental Forest (11,268 ha). Societal source inputs include economic and support services (fuel and electricity consumption) of the U.S. Forest Service (F_1) and the emergy brought in or contributed through tourist activities (F_2).

The Luquillo Experimental Forest in Puerto Rico (Figure 24) is visited by approximately 500,000 tourists per year and is one of the most highly visited forests per unit area in the entire U.S. Forest system (Loudon 1989; CNF 1992). Solar emergy supporting visitor activities was calculated in two parts: 1) the monetary expense incurred by people visiting the forest was calculated and multiplied by the emergy/dollar index for Puerto Rico for island residents or the U.S. for non-island residents (items 9a and 10a); and 2) the energy expended during recreation within the forest was also estimated and converted to solar emergy using estimated solar transformities for human metabolism (items 9b and 10b).



(c)

Solar transformity	114,960 sej/J
Emergy yield ratio	1.11
Emergy investment ratio	10.44

Figure 23. Systems diagram of production of 1 ton of paper products: (a) physical units; (b) solar emergy; (c) resource indices. Calculations given as footnotes.

Figure 23--continued; notes.

Calculations are based on inputs required for entire paper industry in Sweden in 1988, including newspaper, writing paper, kraftpaper, and cardboard production (data from Skogsstyrelsen 1989):

F_1 Wood input: (23.753E+6 m^3/yr) / (6.954E+6 ton/yr, paper) = 3.42 m^3 wood / ton, paper = (1.45 ton, wood / ton, paper) (2.052E+10 J/ton) = (29.83E+9 J/ton) (16000 sej/J; ST for wood chips, Table 15) = 477E+12 sej/ton paper; where YR for wood chips = 1.7 (Table 15), then
F_1 = (1 / 1.7) (477E+12 sej/ton) = 298E+12 sej/ton
I_1 = [(1.7 - 1.0) / (1.7) (477E+12 sej/ton) = 179E+12 sej/ton

F_2 Wood fuels: (0.4E+9 kWh/yr) / (6.954E+6 ton/yr, paper) = (57.52 kWh/ton) (3.6E+6 J/kWh) = 0.207E+9 J/ton (16000 sej/J; ST for wood chips, Table 15) = 3.3E+12 sej/ton; where emergy yield ratio for wood chips = 1.7 (Table 15), then
F_2 = (1 / 1.7) (3.52E+12 sej/ton) = 2.1E+12 sej/ton
I_2 = [(1.7 - 1.0) / (1.7) (3.52E+12 sej/ton) = 1.2E+12 sej/ton

F_3 Chemical pulp inputs: (1.36E+6 ton/yr) (1698E+12 sej/ton; Figure 21) / (6.954E+6 ton/yr, paper) = 332E+12 sej/ton; where YR for chem. pulp = 1.15 (Figure 21), then
F_3 = (1 / 1.15) (332E+12 sej/ton) = 289E+12 sej/ton
I_3 = [(1.15 - 1.0) / (1.15) (332E+12 sej/ton) = 43E+12 sej/ton

F_4 Mechanical pulp inputs: (0.138E+6 ton/yr) (4232E+12 sej/ton; Figure 22) / (6.954E+6 ton/yr, paper) = 83.9E+12 sej/ton; where YR for mech. pulp = 1.03 (Figure 22), then
F_4 = (1 / 1.03) (83.9E+12 sej/ton) = 81E+12 sej/ton
I_4 = [(1.03 - 1.0) / (1.03) (83.9E+12 sej/ton) = 2E+12 sej/ton

F_5 Other fuels: [(0.5) (0.3E+9 kWh/yr) + 4.2E+9 kWh/yr] / (6.954E+6 ton/yr, paper) = (625.6 kWh/ton) (3.6E+6 J/kWh) = 2.252E+9 J/ton (40000 sej/J; intermediate ST for coal) = 90E+12 sej/ton

F_6 Oil: [(.5) (0.1E+9 kWh/yr) + 4.4E+9 kWh/yr] / (6.954E+6 ton/yr, paper) = (654.3 kWh/ton) (3.6E+6 J/kWh) = 2.356E+9 J/ton (47900 sej/J) = 113E+12 sej/ton

F_7 Electricity: [(.5) (0.1E+9 kWh/yr) + 4.8E+9 kWh/yr] / (6.954E+6 ton/yr, paper) = (697.4 kWh/ton) (3.6E+6 J/kWh) = 2.51E+9 J/ton (1.25E+5 sej/J) = 314E+12 sej/ton

F_8 Production costs: (24.43E+9 SEK/yr) / (6.954E+6 ton/yr, paper) = (3513 SEK/ton) / (6.5 SEK/$, 1988) = 540 $/ton (1.5E+12 sej/$) = 843E+12 sej/ton

F_9 Capital costs: (2.98E+9 SEK/yr) / (6.954E+6 ton/yr, paper) = (428.5 SEK/ton) / (6.5 SEK/$, 1988) = 66 $/ton (1.5E+12 sej/$) = 103E+12 sej/ton

Summary of measurements:
I $I_1 + I_2 + I_3 + I_4$ = (179 + 1.2 + 2.4 + 43)E+12 sej/ton = 226E+12 sej/ton
F F_1+... F_9 = (298 + 2.1 + 90 + 113 + 314 + 289 + 81 + 843 + 103)E+12 sej/ton = 2133E+12 sej/ton
Y = I + F = 2359E+12 sej/ton

ST (2359E+12 sej/ton) / (2.052E10 J/ton) = 114,960 sej/J
YR (2359E+12 sej/ton) / (2133E+12 sej/ton) = 1.11
IR (2133E+12 sej/ton) / (226E+12 sej/ton) = 10.44

Table 17. Emergy evaluation of recreation in the Luquillo Experimental Forest, Puerto Rico. Analysis is summarized in Figure 24.

Note	Item	Total Resource units/yr (J, $)	Solar emergy per unit[a]	Solar emergy flow:	
				forest reserve (E+18 sej/yr)	per hectare (E+12 sej/ha/yr)
I	Environmental sources[b]:				
	1. Elfin, cloud forest (412 ha)	---	---	5.4	474.8
	2. Colorado forest (3285 ha)	---	---	20.7	1837.1
	3. Palm forest (1914 ha)	---	---	11.1	9850.9
	4. Tabonuco forest (5657 ha)	---	---	12.4	1100.5
	Total forest reserve (11,268 ha):	---	---	49.6	4397.4
F_1	Economic support services:				
	5. National Forest budget	2,865,000 $	1.64E+12	4.7	418.0
	6. Administration	1,685,000 $	1.64E+12	2.8	245.8
	7. Electricity consumption	2.48E+12 J	1.25E+05	0.3	27.4
	8. Fuel consumption	1.83E+13 J	47900	0.9	77.9
	Total support services:	---	---	8.7	769.1
F_2	Tourism:				
	9. Island residents (386,000 visitors)				
	a. Money spent to get to LEF	2.70E+06 $	1.64E+12	4.4	394.0
	b. Energy expended during recreation	8.42E+11 J	4.81E+06	4.1	359.4
	10. Non-island residents (114,000 visitors)				
	a. Money spent to get to LEF	2.49E+06 $	1.60E+12	4.0	353.2
	b. Energy expended during recreation	2.49E+11 J	8.90E+06	2.2	196.1
	Total recreational sources:			14.7	1302.7
Y	Luquillo Experimental Forest total:	---	---	72.9	6469.2

Summary of measurements:

Emergy yield ratio	3.12
Emergy investment ratio	0.47
Tourism / economic investment	1.69

Table 17--continued; notes.

a. Inputs calculated as available energy are multiplied by solar transformities (***sej***/J) to obtain solar emergy; monetary inputs use ***sej***/$ for regional economy and year of production (Table 2 unless cited otherwise in footnotes.

b. Environmental sources (I) are the sum of transpired rainfall supporting forest production (Table 11) and physical energy of surface water runoff (Table 14).

F_1 Economic support services: data from the 1992 operating budget of Luquillo Experimental Forest (U.S. Forest Service, personal communication):

5. Caribbean National Forest budget, 1992 = 2.865E+6 $/yr

6. International Institute of Tropical Forestry administration = (1.362E+6 $/yr, salary + 3.23E+5 $/yr, fixed costs) = 1.685E+6 $/yr

7. Electricity consumption: 89,404.67 $/yr, cost (0.13 $/kWh, avg. price) (3.6E+6 J/kWh) = 2.48E+12 J/yr

8. Fuel consumption: 39 vehicles operated, consuming 118,357 gal. gasoline in 1994 (Doherty et al. 1994); (118,357 gal/yr) (37,000 kcal/gal, heat content of gas) (4186 J/kcal) = 1.83E+13 J/yr

F_2 Tourism:

9. Island residents:
    a. Money spent: (386,000 persons visited LEF in 1992; CNF 1992) ($7/person/visit) = 2.7E+6 US$

    b. Energy expended during visit = (386,000 p/y) (5 hrs/visit) (2500 kcal/d) / (24 hr/d) (4186 J/kcal) = 8.42E+11 J/yr

    Estimate of solar transformity for Puerto Rico residents:
    Solar emergy-use per capita in P.R., 1992 = 18.4E+15 sej/p/yr (Doherty et al. 1994) / (365 d/y) / (2500 kcal/d) / (4186 J/kcal) = 4.81E+6 sej/J

10. Non-island residents visiting LEF:
    a. Money spent: (114,000 foreigners visited CNF in 1992) / (3,703,200 foreigners visited P.R. in 1992) = 3.1%; $408 spent + $300 est. airfare = $708/foreigner/visit, ($708) (0.031) = $21.80/foreigner/visit (114,000 foreigners) ($21.80/visit) = 2.49E+6 US$

    b. Energy spent by non-island resident during visit = (114,000 p/y) (5 hrs/visit) (2500 kcal/d) / (24 hr/d) (4186 J/kcal) = 2.49E+11 J/yr

    Estimate of solar transformity for U.S. / foreign visitors:
    Solar emergy-use per capita for U.S. in 1992 = 34E+15 sej/p/yr (Odum 1995) / (365 d/y) / (2500 kcal/d) / (4186 J/kcal) = 8.9E+6 sej/J

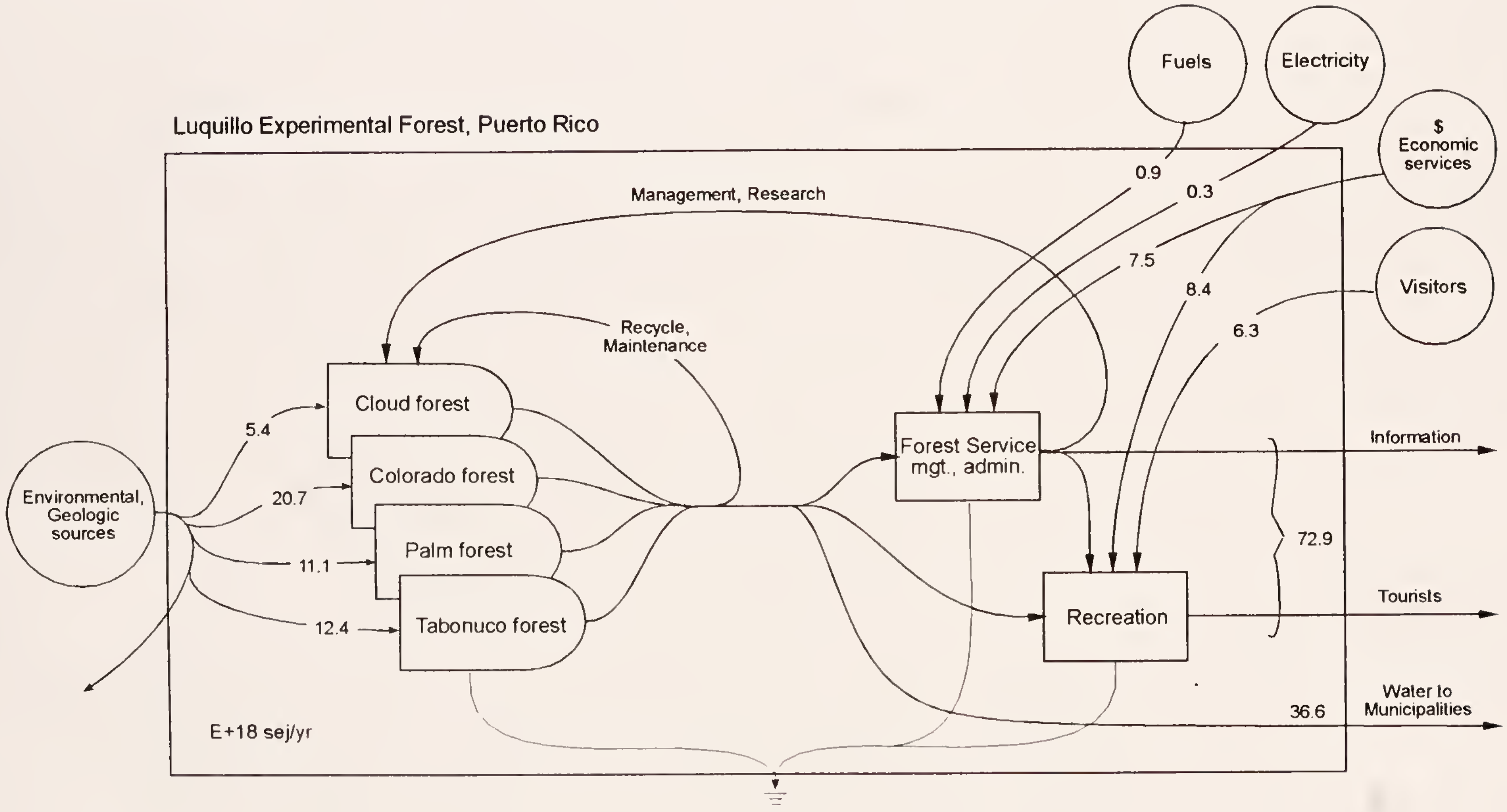


Figure 24. Systems diagram of annual environmental production and economic services supporting multiple-uses in the Luquillo Experimental Forest, Puerto Rico. Refer to Table 17 for calculations.

Forest environmental emergy sources (I) contributed 49.6E+18 sej/yr compared with 8.7E+18 sej/yr contributed through U.S. Forest Service investment and 14.7E+18 sej/yr from tourist activities. An emergy yield ratio of 3.12 was measured, indicating the forest provides a net benefit from tourism. The investment ratio for recreation, or the ratio of the tourist's economic contribution plus the Forest Service management costs to the forest's environmental production measured 0.47. Emergy brought in through tourism (F_2) measured 1.69 more than the economic support services administered by the Forest Service (F_1), indicating a positive net emergy due to recreational use of the forest. Doherty et al. (1994) determined a ratio of undeveloped forest areas to developed recreation areas of 18.0. This analysis estimates that the ratio of environmental emergy (I) to economic support services (F_1) is 5.71, lower due to the high emergy of economic activities.

Emergy Evaluations of Electricity Generation

Gainesville Regional Utilities

Four electric power substations in Gainesville, Florida were evaluated to determine net emergy yields and solar transformities for fuel sources and electric output: Kelly-7, a natural gas-fired 19.5 MW capacity plant (Table 18; Figure 25a); Kelly-8, a natural gas-fired 44 MW capacity plant (Table 19; Figure 25b); Deerhaven-1, a natural gas-fired 81 MW capacity plant (Table 20; Figure 25c); and Deerhaven-2, a coal-fired 218 MW capacity plant (Table 21; Figure 25d).

Table 18. Emergy evaluation of natural gas-fired electricity production at a 19.5 MW capacity plant (Kelly 7 Station) in Gainesville, Florida.[a] Analysis is summarized in Figure 25a.

Note	Item	Resource units/yr (J, $)	Solar emergy per unit[b]	Solar emergy flow (E+18 sej/yr)
Fuel source:				
1.	Natural gas	2.89E+14 J	34800	10.10
2.	Oil	1.30E+12 J	40200	0.05
3.	Fuel cost	7.45E+05 $	1.60E+12	1.19
Y_1	Purchased fuels	2.91E+14 J	ST_1	11.34
Electricity generation:				
4.	Human services	2.26E+05 $	1.60E+12	0.36
5.	Capital costs	1.29E+05 $	1.27E+13	1.64
6.	Interest	2.52E+05 $	1.60E+12	0.41
Y_2	Electricity	7.12E+13 J	ST_2	13.70

Summary of measurements:

Solar transformity:		
ST_1	Fuel source	38,936 sej/J
ST_2	Electricity	192,498 sej/J
Emergy yield ratio:		
YR_1	Fuel source	9.53
YR_2	Electricity	3.81
Emergy investment ratio:		
IR_2	Fuel source	0.12
IR_2	Electiricity	0.36

Notes.

a. Data supplied by Gainesville Regional Utilities (personal communication) for 1993

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej*/J); monetary inputs use *sej*/$ for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

Table 18--continued.

1. Natural gas: (266,700,000 cf/yr) (1027.7 Btu/cf) (1055 J/Btu) = 2.89E+14 J/yr

2. Oil: (number 6 oil, 194 bbl/yr) (42 gal/bbl) (151,420.4 Btu/gal) (1055 J/Btu) = 1.30E+12 J/yr

3. Fuel cost: 745,000 \$/yr

Y_1 Fuel source: items 1+2 = 2.91E+14 J/yr

4. Human services: (operating, maintenance costs, 11.41 \$/MWhe) (19,782 MWhe/yr; Y_2 below) = 225,713 \$/yr

5. Capital costs: (4,639,000 \$, 1961 construction costs) / (36 yrs life expectancy) = 128,861 \$/yr; 1961 U.S. emergy/dollar ratio = 1.27E+13 sej/\$ (Odum 1995)

6. Annual interest paid on loans: (4.5% book cost; item 5 above + annual fuel and operations costs; items 3 and 4 above): (0.045/yr) (4,639,000 \$ + 970,713 \$) = 252,437 \$/yr

Y_2 Electricity generation: 19,782 MWh/yr (3.60E+09 J/MWh) = 7.12E+13 J/yr

Solar transformity:
ST_1 (1.13E+19 sej/yr) / (2.91E+14 J/yr) = 38,936 sej/J
ST_2 (1.37E+19 sej/yr) / (7.12E+13 J/yr) = 192,498 sej/J

Emergy yield ratio:
YR_1 (Y_1) / (item 3) = (11.34E+18 sej/yr) / (1.19E+18 sej/yr) = 9.53
YR_2 (Y_2) / (items 3+... 6) = (13.75E+18 sej/yr) / (3.60E+18 sej/yr) = 3 81

Emergy investment ratio:
IR_1 (item 3) / (items 1+2) = (1.19E+18 sej/yr) / (10.15E+18 sej/yr) = 0.12
IR_2 (items 3+...6) / (items 1+2) = (3.60E+18 sej/yr) / (10.15E+18 sej/yr) = 0.36

Table 19. Emergy evaluation of natural gas-fired electricity production at a 44 MW capacity plant (Kelly 8 Station) in Gainesville, Florida.[a] Analysis is summarized in Figure 25b.

Note	Item	Resource units/yr (J, $)	Solar emergy per unit[b]	Solar emergy flow (E+18 sej/yr)
Fuel source:				
1.	Natural gas	8.69E+14 J	34800	30.20
2.	Oil	1.32E+13 J	40200	0.53
3.	Fuel cost	2.36E+06 $	1.60E+12	3.78
Y_1	Purchased fuels	8.82E+14 J	ST_1	34.51
Electricity generation:				
4.	Human services	7.48E+05 $	1.60E+12	1.20
5.	Capital costs	2.89E+05 $	1.03E+13	2.98
6.	Interest	6.09E+05 $	1.60E+12	0.97
Y_2	Electricity	2.36E+14 J	ST_2	39.70

Summary of measurements:

Solar transformity:		
ST_1	Fuel source	34,841 sej/J
ST_2	Electricity	168,335 sej/J
Emergy yield ratio:		
YR_1	Fuel source	9.13
YR_2	Electricity	4.44
Emergy investment ratio:		
IR_2	Fuel source	0.12
IR_2	Electinicity	0.29

Notes.

a. Data supplied by Gainesville Regional Utilities (personal communication) for 1993.

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej/J*); monetary inputs use *sej/$* for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

Table 19--continued.

1. Natural gas: (801,340,000 cf/yr) (1027.7 Btu/cf) (1055 J/Btu) = 8.69E+14 J/yr

2. Oil: (number 6 oil, 1973 bbl/yr) (42 gal/bbl) (151,420.4 Btu/gal) (1055 J/Btu) = 1.32E+13 J/yr

3. Fuel cost: 2.364,000 \$/yr

Y_1 Fuel source: items 1+2 = 8.82E+14 J/yr

4. Human services: (operating, maintenance costs, 11.41 \$/MWhe) (65,509 MWhe/yr; Y_2 below) = 747,458 \$/yr

5. Capital costs: (10,413,000 \$, 1965 construction costs) / (36 yrs life expectancy) = 289,250 \$/yr; 1965 U.S. emergy/dollar ratio = 1.03E+13 sej/\$ (Odum 1995)

6. Annual interest paid on loans: [4.5% (book cost; item 5 above + annual fuel and operations costs; items 3 and 4 above)]: (0.045/yr) (10,413,000 \$ + 3,111,458 \$) = 608,601 \$/yr

Y_2 Electricity generation: 65,509 MWh/yr (3.60E+09 J/MWh) = 2.36E+14 J/yr

Solar transformity:
ST_1 (3.45E+19 sej/yr) / (8.82E+14 J/yr) = 34,841 sej/J
ST_2 (3.97E+19 sej/yr) / (2.36E+14 J/yr) = 168,335 sej/J

Emergy yield ratio:
YR_1 (Y_1) / (item 3) = (34.51E+18 sej/yr) / (3.78E+18 sej/yr) = 9.31
YR_2 (Y_2) / (items 3+... 6) = (39.66E+18 sej/yr) / (8.93E+18 sej/yr) = 4.44

Emergy investment ratio:
IR_1 (item 3) / (items 1+2) = (3.78E+18 sej/yr) / (30.73E+18 sej/yr) = 0.12
IR_2 (items 3+...6) / (items 1+2) = (8.93E+18 sej/yr) / (30.73E+18 sej/yr) = 0.29

Table 20. Emergy evaluation of natural gas-fired electricity production at an 81 MW capacity plant (Deerhaven 1 Station) in Gainesville, Florida.[a] Analysis is summarized in Figure 25c.

Note	Item	Resource units/yr (J, $)	Solar emergy per unit[b]	Solar emergy flow (E+18 sej/yr)
Fuel source:				
1.	Natural gas	2.18E+15 J	34800	75.80
2.	Oil	5.57E+13 J	40200	2.24
3	Fuel cost	6.03E+06 $	1.60E+12	9.65
Y_1	Purchased fuels	2.23E+15 J	ST_1	87.69
Electricity generation:				
4.	Human services	7.81E+05 $	1.60E+12	1.25
5.	Capital costs	5.46E+05 $	7.00E+12	3.83
6.	Interest	1.80E+06 $	1.60E+12	2.88
Y_2	Electricity generation	6.31E+14 J	ST_2	95.60

Summary of measurements:

Solar transformity:		
ST_1	Fuel source	39,225 sej/J
ST_2	Electricity	151,604 sej/J
Emergy yield ratio:		
YR_1	Fuel source	9.09
YR_2	Electricity	5.43
Emergy investment ratio:		
IR_2	Fuel source	0.12
IR_2	Electiricity	0.23

Notes.

a. Data supplied by Gainesville Regional Utilities (personal communication) for 1993.

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej*/J); monetary inputs use *sej*/$ for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

Table 20--continued.

1. Natural gas: (2,006,120,000 cf/yr) (1028.7 Btu/cf) (1055 J/Btu) = 2.18E+15 J/yr

2. Oil: (number 2 oil, 6885 gal/yr) (139731.9 Btu/gal) = 9.62E+08 Btu/yr; (number 6 oil, 8165 bbl/yr) (42 gal/bbl) (151026.2 Btu/gal) = 5.18E+10 Btu/yr; total oil = (9.62 +518.0)E+08 Btu/yr (1055 J/Btu) = 5.57E+13 J/yr

3. Fuel cost: 6,029,000 \$/yr

Y_1 Fuel source: items 1+2 = 2.23E+15 J/yr

4. Human services: (operating, maintenance costs, 4.46 \$/MWhe) (175,185 MWhe/yr; Y_2 below) = 781,325 \$/yr

5. Capital costs: (19,687,000 \$, 1972 construction costs) / (36 yrs life expectancy) = 546,861 \$/yr; 1972 U.S. emergy/dollar ratio = 7.00E+12 sej/\$ (Odum 1995)

6. Annual interest paid on loans: (6.8% book cost; item 5 above + annual fuel and operations costs; items 3 and 4 above): (0.068/yr) (19,687,000 \$ + 6,810,325 \$) = 1,801,818 \$/yr

Y_2 Electricity generation: 175,185 MWh/yr (3.60E+09 J/MWh) = 6.31E+14 J/yr

Solar transformity:
ST_1 (8.77E+19 sej/yr) / (2.23E+15 J/yr) = 39,255 sej/J
ST_2 (9.56E+19 sej/yr) / (6.31E+14 J/yr) = 151,604 sej/J

Emergy yield ratio:
YR_1 (Y_1) / (item 3) = (87.7E+18 sej/yr) / (9.65E+18 sej/yr) = 9.09
YR_2 (Y_2) / (items 3+... 6) = (95.6E+18 sej/yr) / (17.61E+18 sej/yr) = 5.43

Emergy investment ratio:
IR_1 (item 3) / (items 1+2) = (9.65E+18 sej/yr) / (78.04E+18 sej/yr) = 0.12
IR_2 (items 3+...6) / (items 1+2) = (17.61E+18 sej/yr) / (78.04E+18 sej/yr) = 0.23

Table 21. Emergy evaluation of coal-fired electricity production at a 218 MW capacity plant (Deerhaven 2 Station) in Gainesville, Florida.[a] Analysis is summarized in Figure 25d.

Note	Item	Resource units/yr (J, $)	Solar emergy per unit[b]	Solar emergy flow (E+18 sej/yr)
Fuel source:				
1	Coal	1.49E+16 J	29000	431.10
2	Natural Gas	2.41E+14 J	34800	8.40
3	Fuel cost	2.58E+07 $	1.60E+12	41.35
Y_1	Purchased fuel	1.51E+16 J	ST_1	480.85
Electricity generation:				
4	Human services	6.06E+06 $	1.60E+12	9.70
5	Capital costs	5.00E+06 $	2.70E+13	13.49
6	Interest	1.44E+07 $	1.60E+12	23.05
Y_2	Electricity	4.89E+15 J	ST_2	527.05

Summary of measurements:

Solar transformity:		
ST_1	Fuel source	31,830 sej/J
ST_2	Electricity	107,736 sej/J
Emergy yield ratio:		
YR_1	Fuel source	11.63
YR_2	Electricity	6.02
Emergy investment ratio:		
IR_2	Fuel source	0.09
IR_2	Electiricity	0.20

Notes.

a. Data supplied by Gainesville Regional Utilities (personal communication) for 1993.

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej*/J); monetary inputs use *sej*/$ for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

Table 21--continued.

1. Coal: (530,750 tons/yr) (2000 lbs/ton) (13273.02 Btu/lb) (1055 J/Btu) = 1.49E+16 J/yr

2. Natural gas: (222,300,000 cf/yr) (1028.7 Btu/cf) (1055 J/Btu) = 2.41E+14 J/yr

3. Fuel cost: 25,844,000 \$/yr

Y_1 Fuel source: items 1+2 = 1.51E+16 J/yr

4. Human services· (operating, maintenance costs, 4.46 \$/MWhe) (1,358,896 MWhe/yr; Y_2 below) = 6,060,676 \$/yr

5. Capital costs: (179,911,000 \$, 1981 construction costs) / (36 yrs life expectancy) = 4,997,528 \$/yr; 1981 U.S. emergy/dollar ratio = 2.70E+12 sej/\$ (Odum 1995)

6. Annual interest paid on loans: [6.8% (book cost; item 5 above + annual fuel and operations costs; items 3 and 4 above)]: (0.068/yr) (179,911,000 \$ + 31,904,676 \$) = 14,403,466 \$/yr

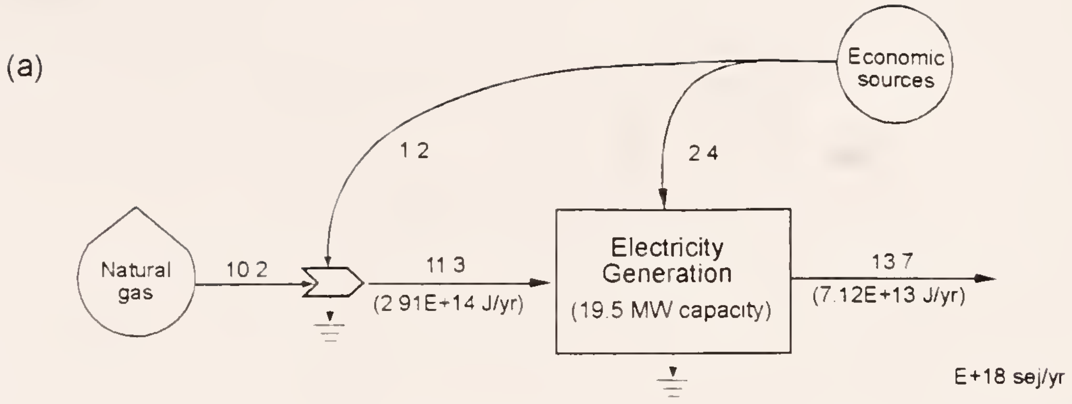
Y_2 Electricity generation: 1,358,896 MWh/yr (3.60E+09 J/MWh) = 4.89E+15E+14 J/yr

Solar transformity:
ST_1 (4.81E+20 sej/yr) / (1.51E+16 J/yr) = 31,830 sej/J
ST_2 (5.27E+20 sej/yr) / (4.89E+15 J/yr) = 107,736 sej/J

Emergy yield ratio:
YR_1 (Y_1) / (item 3) = (480.851E+18 sej/yr) / (41.35E+18 sej/yr) = 11.63
YR_2 (Y_2) / (items 3+... 6) = (527.05E+18 sej/yr) / (87.59E+18 sej/yr) = 6.02

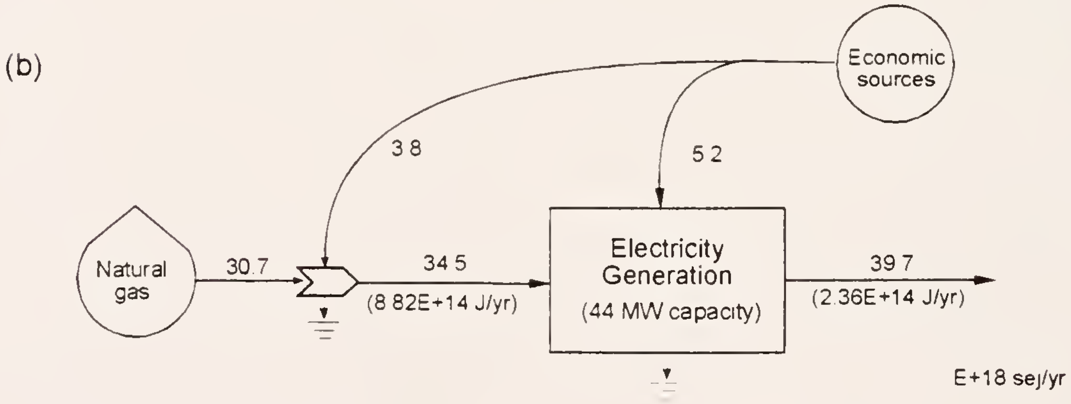
Emergy investment ratio:
IR_1 (item 3) / (items 1+2) = (41.35E+18 sej/yr) / (439.50E+18 sej/yr) = 0.09
IR_2 (items 3+...6) / (items 1+2) = (87.59E+18 sej/yr) / (439.50E+18 sej/yr) = 0.20

(a)



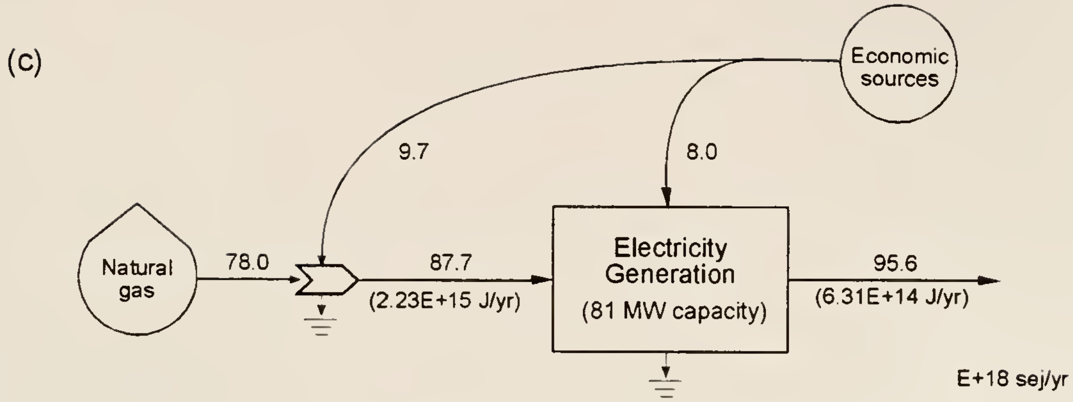
	Fuel source	Electricity
Solar transformity	38,936 sej/J	192,498 sej/J
Emergy yield ratio	9.53	3.81
Emergy investment ratio	0.12	0.36

(b)

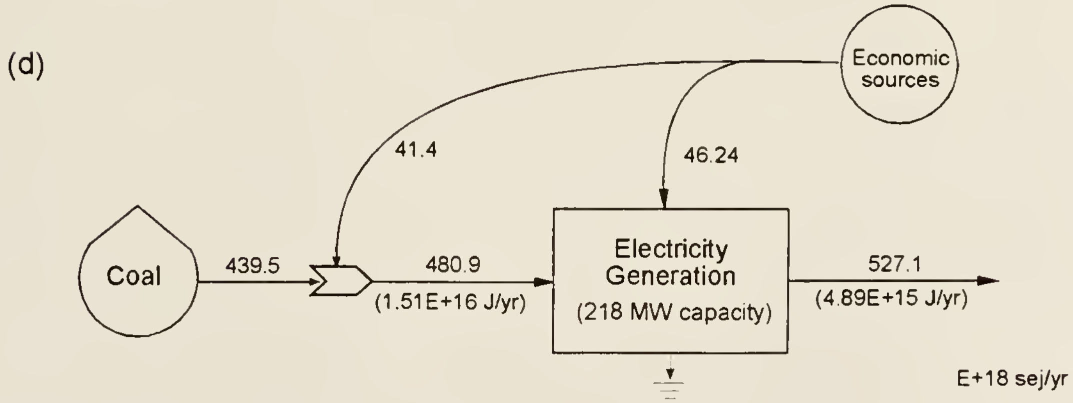


	Fuel source	Electricity
Solar transformity	34,841 sej/J	168,335 sej/J
Emergy yield ratio	9.13	4.44
Emergy investment ratio	0.12	0.29

Figure 25. Systems diagrams of electricity production at four generator substations in Gainesville, Florida. (a) natural gas-fired generation, 19.5 MW capacity (Kelly 7 Station) (Table 18); (b) natural gas-fired generation, 44 MW capacity (Kelly 8 Station) (Table 19).



	Fuel source	Electricity
Solar transformity	39,255 sej/J	151,604 sej/J
Emergy yield ratio	9.09	5.43
Emergy investment ratio	0.12	0.23



	Fuel source	Electricity
Solar transformity	31,830 sej/J	107,736 sej/J
Emergy yield ratio	11.63	6.02
Emergy investment ratio	0.09	0.20

Figure 25. (continued). Systems diagrams of electricity production at four generator substations in Gainesville, Florida: (c) natural gas-fired, 81 MW capacity (Deerhaven 1 Station) (Table 20); (d) coal-fired generation, 218 MW capacity (Deerhaven 2 Station) (Table 21).

In all four case studies, supplemental fuels consumed in addition to the primary fuel were less than 3% of the total fuel emergy.

Solar transformities for purchased natural gas, based on environmental emergy plus the emergy of the fuel cost to the utility, averaged 37,680 sej/J with an average emergy yield ratio of about 9.25 (Figure 25). Solar transformities for natural gas-fired electricity production ranged from 151,604 sej/J to 192,498 sej/J, increasing with decreasing plant capacity. Emergy yield ratios correspondingly increased with increasing plant capacity from 3.81 for the 19.5 MW capacity plant (Figure 25a) to 5.43 for the 81 MW capacity substation (Figure 25c). Coal-fired electricity generation at Deerhaven-2, the largest (218 MW) capacity plant had the lowest solar transformity (107,736 sej/J) and the highest emergy yield ratio (6.02) for the four case studies (Figure 25d). An emergy yield ratio for purchased coal measured 11.63, the highest measure of a primary fuel source derived from this study.

Electricity Production in Thailand

Using data from the Dendro Thermal Power Programme of Thailand (NEA/FEP 1990), four case studies of electricity production were evaluated: natural gas (Table 22); coal (Table 23); oil (Table 24); and lignite (Table 25). All four overview analyses are summarized in Figure 26. Each analysis is based on 1 MWh electricity production from existing operations. Estimates of transmission costs and losses are based on average plant distances to municipal users. Transformities and resource indices could not be calculated for fuel sources since fuel costs were not separated from operating costs.

Table 22. Emergy evaluation of natural gas-fired electricity production in Thailand.[a] Analysis is summarized in Figure 26a.

Note	Item	Resource units/MWhe (J, $)	Solar emergy per unit[b]	Solar emergy per MWH electr. (E+12 sej/MWhe)
1.	Imported natural gas	1.27E+10 J	34800	443.18
2.	Fuel and operations costs	29.20 $	3.69E+12	107.75
3.	Capital costs	11.60 $	3.69E+12	42.80
Y_1	Electricity generation (1 MWh)	3.60E+09 J	ST_1	593.74
4.	Transmission costs	10.80 $	3.69E+12	39.85
Y_2	Electricity delivered to user	2.92E+09 J	ST_2	633.59

Summary of measurements:

Solar transformity:		
ST_1	Electricity generation	164,927 sej/J
ST_2	Electricity delivered to user	216,745 sej/J
Emergy yield ratio:		
YR_1	Electricity generation	3.94
YR_2	Electricity delivered to user	3.33
Emergy investment ratio:		
IR_1	Electricity generation	0.34
IR_2	Electricity delivered to user	0.43

Notes.

a. Calculated for 1 MWh electricity; data from the Dendro Thermal Power Programme of Thailand (NEA/FEP 1990).

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej*/J); monetary inputs use *sej*/$ for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

1. Natural gas: Energy efficiency factor (0.283) for electricity generated per unit natural gas is from GRU 1993; (3.54 MWh-natural gas/MWh-electricity) (3.60E+09 J/MWh) = 1.27E+10 J/MWhe

2. Fuel, operations costs: (0.73 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 29.20 $/MWhe

3. Capital costs: (0.29 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 11.60 $/MWhe

Table 22--continued.

Y_1 Electricity generation: (1 MWhe) (3.60E+09 J/MWh) = 3.60E+09 J

4. Transmission costs: $ cost per kWh electricity delivered is based on distance from power plant to rural substation; (0.27 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 10.80 $/MWhe

Y_2 Electricity delivered to user: 18.8% transmission loss; (0.188) (1 MWhe) (3.60E+09 J/MWh) = 2.92E+09 J

Solar transformity:
ST_1 Electricity = (5.937E+14 sej/MWhe) / (3.60E+9 J/MWhe) = 164,927 sej/J
ST_2 Electricity delivered to user = (6.336E+14 sej/MWhe) / (2.92E+9 J/MWhe) = 216,745 sej/J

Emergy yield ratio:
YR_1 Y_1 / (items 2, 3) = (594E+12 sej/MWhe) / (108 + 43)E+12 sej/MWhe = 3.94
YR_2 Y_2 / (items 2, 3, 4) = (634E+12 sej/MWhe) / (108 + 43 + 40)E+12 sej/MWhe = 3.33

Emergy investment ratio:
IR_1 (items 2, 3) / (item 1) = (108 + 43)E+12 sej/MWhe / (443E+12 sej/MWhe) = 0.34
IR_2 (items 2, 3, 4) / (item 1) = (108 + 43 + 40)E+12 sej/MWhe / (443E+12 sej/MWhe) = 0.43

Table 23. Emergy evaluation of coal-fired electricity production in Thailand.[a] Analysis is summarized in Figure 26b.

Note	Item	Resource units/MWhe (J, $)	Solar emergy per unit[b]	Solar emergy per MWH electr. (E+12 sej/MWhe)
1.	Imported coal	1.00E+10 J	29000	290.00
2.	Fuel and operations costs	29.60 $	3.69E+12	109.22
3.	Capital costs	15.60 $	3.69E+12	57.56
Y_1	Electricity generation (1 MWh)	3.60E+09 J	ST_1	456.79
4.	Transmission costs	11.60 $	3.69E+12	42.80
Y_2	Electricity delivered to user	2.87E+09 J	ST_2	499.59

Summary of measurements:

Solar transformity:

ST_1	Electricity generation	126,886 sej/J
ST_2	Electricity delivered to user	174,341 sej/J

Emergy yield ratio:

YR_1	Electricity generation	2.74
YR_2	Electricity delivered to user	2.38

Emergy investment ratio:

IR_1	Electricity generation	0.58
IR_2	Electricity delivered to user	0.72

Notes.

a Calculated for 1 MWh electricity; data from the Dendro Thermal Power Programme of Thailand (NEA/FEP 1990).

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej*/J); monetary inputs use *sej*/$ for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

1 Coal: Energy efficiency factor (0.360); (2.78 MWh-coal/MWh-electricity) (3.60E+09 J/MWh) = 1.00E+10 J/MWhe

2. Fuel, operations costs: (0.74 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 29.60 $/MWhe

3. Capital costs: (0.39 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 15.60 $/MWhe

Table 23--continued

Y_1 Electricity generation: (1 MWhe) (3.60E+09 J/MWh) = 3.60E+09 J

4. Transmission costs: \$ cost per kWh electricity delivered is based on distance from power plant to rural substation; (0.29 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 11.60 \$/MWhe

Y_2 Electricity delivered to user: 20.4% transmission loss; (0.204) (1 MWhe) (3.60E+09 J/MWh) = 2.87E+09 J

Solar transformity:
ST_1 Electricity = (4.568E+14 sej/MWhe) / (3.60E+9 J/MWhe) = 126,886 sej/J
ST_2 Electricity delivered to user = (4.996E+14 sej/MWhe) / (2.87E+9 J/MWhe) = 174,341 sej/J

Emergy yield ratio:
YR_1 Y_1 / (items 2, 3) = (457E+12 sej/MWhe) / (109 + 58)E+12 sej/MWhe = 2.74
YR_2 Y_2 / (items 2, 3, 4) = (500E+12 sej/MWhe) / (109 + 58 + 43)E+12 sej/MWhe = 2.38

Emergy investment ratio:
IR_1 (items 2, 3) / (item 1) = (109 + 58)E+12 sej/MWhe / (290E+12 sej/MWhe) = 0.58
IR_2 (items 2, 3, 4) / (item 1) = (109 + 58 + 43)E+12 sej/MWhe / (290E+12 sej/MWhe) = 0.72

Table 24. Emergy evaluation of oil-fired electricity production in Thailand.[a] Analysis is summarized in Figure 26c.

Note	Item	Resource units/MWhe (J, $)	Solar emergy per unit[b]	Solar emergy per MWH electr. (E+12 sej/MWhe)
1.	Imported oil	9.47E+09 J	40200	380.84
2.	Fuel and operations costs	35.60 $	3.69E+12	131.36
3.	Capital costs	10.80 $	3.69E+12	39.85
Y_1	Electricity generation (1 MWh)	3.60E+09 J	ST_1	552.06
4.	Transmission costs	11.20 $	3.69E+12	41.33
Y_2	Electricity delivered to user	2.90E+09 J	ST_2	593.39

Summary of measurements:

Solar transformity:		
ST_1	Electricity generation	153,349 sej/J
ST_2	Electricity delivered to user	204,503 sej/J
Emergy yield ratio:		
YR_1	Electricity generation	3.22
YR_2	Electricity delivered to user	2.79
Emergy investment ratio:		
IR_1	Electricity generation	0.45
IR_2	Electricity delivered to user	0.56

Notes.

a. Calculated for 1 MWh electricity; data from the Dendro Thermal Power Programme of Thailand (NEA/FEP 1990).

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej/J*); monetary inputs use *sej/$* for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

1. Oil: Energy efficiency factor (0.380); (2.63 MWh-oil/MWh-electricity) (3.60E+09 J/MWh) = 9.47E+09 J/MWhe

2. Fuel, operations costs: (0.89 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 35.60 $/MWhe

3. Capital costs: (0.27 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 10.80 $/MWhe

Table 24--continued.

Y_1 Electricity generation: (1 MWhe) (3.60E+09 J/MWh) = 3.60E+09 J

4. Transmission costs: $ cost per kWh electricity delivered is based on distance from power plant to rural substation; (0.28 Baht/kWh) / (25 Baht/$, 1987) (1000 MWh/kWh) = 11.20 $/MWhe

Y_2 Electricity delivered to user: 19.4% transmission loss; (0.194) (1 MWhe) (3.60E+9 J/MWh) = 2.90E+9 J

Solar transformity:
ST_1 Electricity = (5.52E+14 sej/MWhe) / (3.60E+9 J/MWhe) = 153,349 sej/J
ST_2 Electricity delivered to user = (5.93E+14 sej/MWhe) / (2.90E+9 J/MWhe) = 164,829 sej/J

Emergy yield ratio:
YR_1 Y_1 / (items 2, 3) = (552E+12 sej/MWhe) / (131 + 40)E+12 sej/MWhe = 3.22
YR_2 Y_2 / (items 2, 3, 4) = (593E+12 sej/MWhe) / (131 + 40 + 41)E+12 sej/MWhe = 2.79

Emergy investment ratio:
IR_1 (items 2, 3) / (item 1) = (131 + 40)E+12 sej/MWhe / (552E+12 sej/MWhe) = 0.45
IR_2 (items 2, 3, 4) / (item 1) = (131 + 40 +41)E+12 sej/MWhe / (593E+12 sej/MWhe) = 0.56

Table 25. Emergy evaluation of lignite-fired electricity production in Thailand.[a] Analysis is summarized in Figure 26d.

Note	Item	Resource units/MWhe (J, $)	Solar emergy per unit[b]	Solar emergy per MWH electr. (E+12 sej/MWhe)
1.	Domestic lignite	1.01E+10 J	37000	372.07
2.	Mining costs	9.00 $	3.69E+12	33.21
3.	Fuel and operations costs	27.20 $	3.69E+12	100.37
4.	Capital costs	12.00 $	3.69E+12	44.28
Y_1	Electricity generation (1 MWh)	3.60E+09 J	ST_1	549.92
5.	Transmission costs	8.00 $	3.69E+12	29.52
Y_2	Electricity delivered to user	2.99E+09 J	ST_2	579.45

Summary of measurements:

Solar transformity:

ST_1	Electricity generation	152,757 sej/J
ST_2	Electricity delivered to user	193,691 sej/J

Emergy yield ratio:

YR_1	Electricity generation	3.09
YR_2	Electricity delivered to user	2.79

Emergy investment ratio:

IR_1	Electricity generation	0.48
IR_2	Electricity delivered to user	0.56

Notes.

a. Calculated for 1 MWh electricity; data from the Dendro Thermal Power Programme of Thailand (NEA/FEP 1990).

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej/J*); monetary inputs use *sej/$* for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

1. Lignite: Energy efficiency factor (0.358); (2.79 MWh-lignite/MWh-electricity) (3.60E+09 J/MWh) = 1.01E+10 J/MWhe

2. Mining costs: (224 Baht/ton) / (25 Baht/$, 1987) / (1.00E+10 J/ton; Odum et al. 1987) (3.60E+06 J/MWh) / (0.358) = 9.00 $/MWhe

Table 25--continued.

3. Fuel, operation costs: (0.68 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 27.20 \$/MWhe

4. Capital costs: (0.30 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 12.00 \$/MWhe

Y_1 Electricity generation: (1 MWhe) (3.60E+09 J/MWh) = 3.60E+09 J

5. Transmission costs: \$ cost per kWh electricity delivered is based on distance from power plant to rural substation; (0.20 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 8.00 \$/MWhe

Y_2 Electricity delivered to user: 16.9% transmission loss; (0.169) (1 MWhe) (3.60E+09 J/MWh) = 2.99E+09 J

Solar transformity:
ST_1 Electricity = (5.499E+14 sej/MWhe) / (3.60E+9 J/MWhe) = 152,757 sej/J
ST_2 Electricity delivered to user = (5.794E+14 sej/MWhe) / (2.99E+9 J/MWhe) = 193,691 sej/J

Emergy yield ratio:
YR_1 Y_1 / (items 2, 3, 4) = (550E+12 sej/MWhe) / (33 + 100 + 44)E+12 sej/MWhe = 3.09
YR_2 Y_2 / (items 2, 3, 4, 5) = (579E+12 sej/MWhe) / (33 + 100 + 44 + 30)E+12 sej/MWhe = 2.79

Emergy investment ratio:
IR_1 (items 2, 3, 4) / (item 1) = (33 + 100 + 44)E+12 sej/MWhe / (372E+12 sej/MWhe) = 0.48
IR_2 (items 2, 3, 4, 5) / (item 1) = (33+100+44+30)E+12 sej/MWhe / (372E+12 sej/MWhe) = 0.56

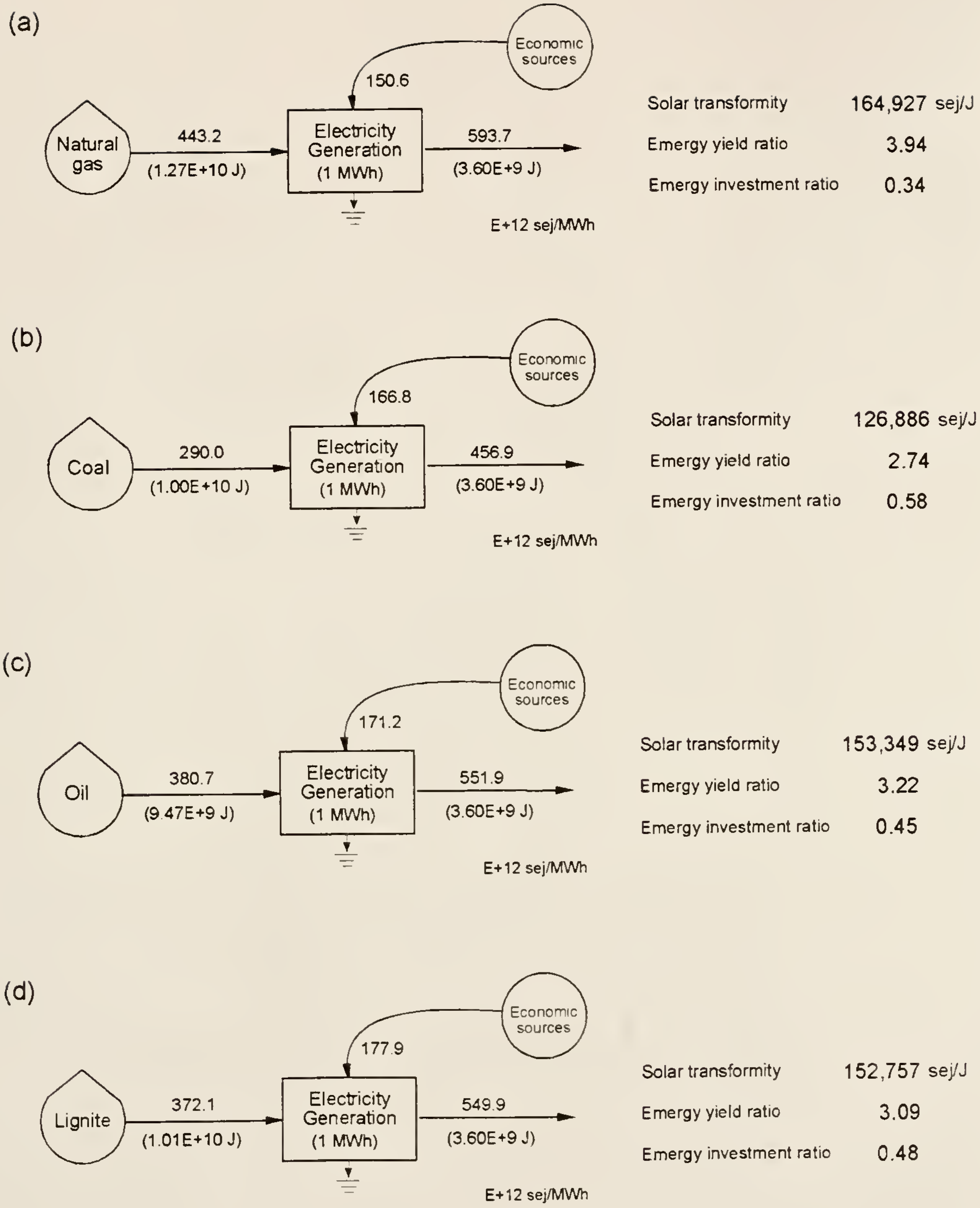


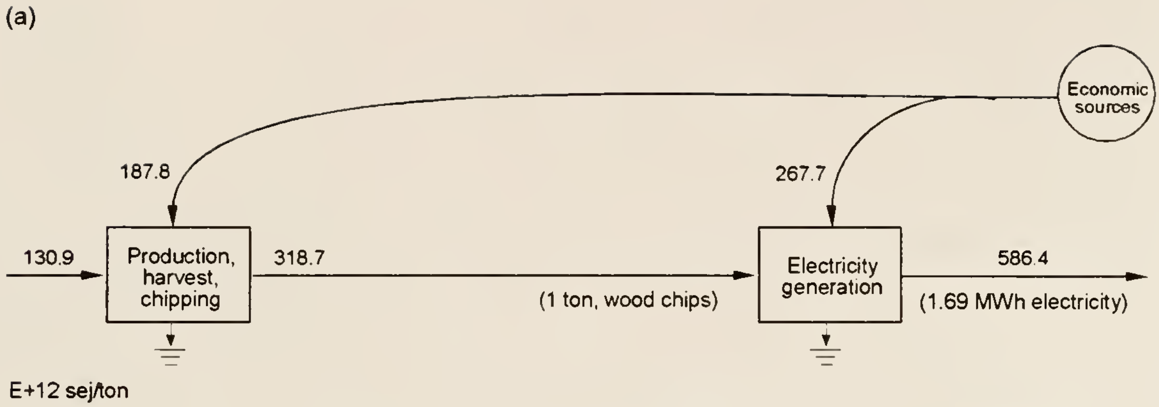
Figure 26. Aggregate systems diagrams and related resource indices for electricity production (1 MWh) using four non-renewable fuel sources in Thailand: (a) natural gas-fired generation (Table 22); (b) coal-fired generation (Table 23); (c) oil-fired generation (Table 24); (d) lignite-fired generation (Table 25).

A solar transformity for natural gas-fired electricity production fell within the range of values for electricity from natural gas in the Gainesville studies (Figure 25a, b, c), and measured the highest of the four case studies in Thailand (Figure 26a). Emergy yield ratios ranged from 3.94 for natural gas-fired electricity (Figure 26a) to 2.74 for electricity generated from imported coal (Figure 26b). Transmission losses were lowest for electricity delivered from plants burning domestic lignite (Table 25) increasing the solar transformity 22% and reducing the emergy yield ratio 11% for electricity delivered to rural users. Other plants averaged 34% increases in transformities based on further distances between substations and rural users.

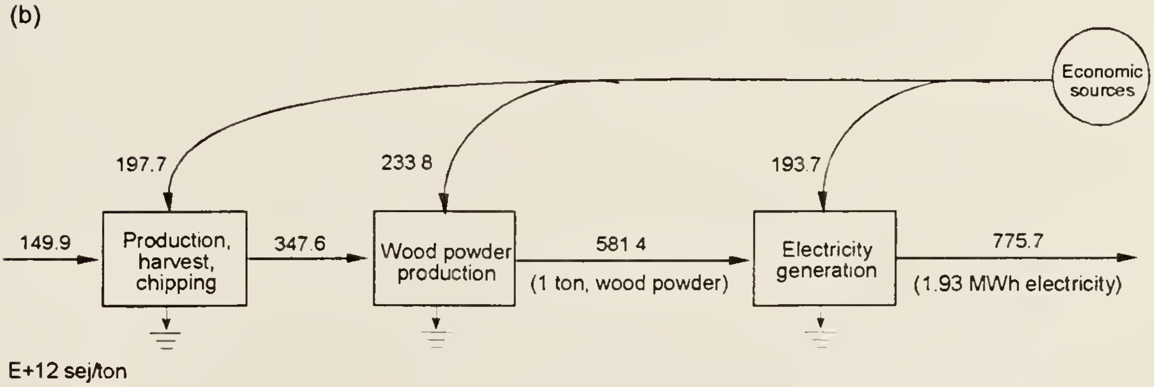
Wood-fired Electricity Generation

Theoretical electricity production from wood chips and wood powder is evaluated in Figure 27. Analyses are based on production of mechanical, useful heat derived from woodfuels in Sweden, evaluated in Tables 15 and 16. Additional inputs required were estimated by the price of the woodfuel at the plant after costs already incurred in the development of the woodfuel were subtracted. Wood chips (Figure 27a) could produce 1.69 MWh-electricity/ton or an energy efficiency of 0.30 (30% net energy output).

Wood powder (Figure 27b) would yield about 1.93 MWh-electricity/ton or about 34% net energy output. A solar transformity measured 96,382 sej/J for electricity from wood chips and 111,490 sej/J from wood powder. Because of the additional inputs required to upgrade wood chips to wood powder, the emergy



	Wood chips	Electricity
Solar transformity	15,557 sej/J	96,382 sej/J
Emergy yield ratio	1.70	1.29
Emergy investment ratio	1.44	3.48



	Wood powder	Electricity
Solar transformity	29,844 sej/J	111,490 sej/J
Emergy yield ratio	1.35	1.24
Emergy investment ratio	2.88	4.17

Figure 27. Systems diagrams of theoretical electricity production using alternative woodfuels in Sweden (based on 1 ton fuelwood conversion): (a) wood chip-fired generation; (b) wood powder-fired generation. Calculations given as footnotes.

Figure 27--continued; notes.

Analyses are based upon fuelwood [(a) wood chips, Table 15; (b) wood powder, Table 16)] produced from silviculturally grown spruce/pine in southern Sweden (Table 4).

(a) Theoretical electricity generation from wood chips:

I Environmental sources: (59.1E+12 sej/ha/yr; Table 15) / (1.061 m^3/ha/yr) (2.35 m^3/ton) = 1.31E+14 sej/ton

$F_{1\text{-}3}$ Economic inputs to wood chip production = F_1+F_2+F_3 (Table 15) = (84.8E+12 sej/ha/yr) / (1.061 m^3/ha/yr) (2.35 m^3/ton) = 1.88E+14 sej/ton

F_4 Economic inputs to electric generation:
(est. using district plant operations/maintenance costs + price of wood chips):

a. Incurred costs of chip production (to avoid double counting of inputs) = silviculture costs (4.90 $ton) + harvest costs (40.60 $/ton) + delivery costs (11.22 $/ton) = 103.18 $/ton;

Price of wood chips delivered at district plant est. using ratio of powder price/powder cost (see below) = (1040 SEK/ton) / (765 SEK/ton) = 1.36; then price of wood chips = (103.18 $/ton) (1.36) = 140.32 $/ton;

Unaccounted costs = (140.32 - 103.18) $/ton = (37.15 $/ton) (1.5E+12 sej/$) = 5.57E+13 sej/ton

b. Operations, maintenance, fuels: (95.7E+12 sej/ha/yr; Table 15) / (1.061 m^3/ha/yr) (2.35 m^3/ton) = 2.12E+14 sej/ton

Economic inputs to electric prod. = a + b = (0.557 + 2.12)E+12 sej/ton = 2.68E+14 sej/ton

Y_4 [I + (F_1+... F_3) + F_4] = (1.31 + 1.88 + 2.68)E+14 sej/ton = 5.86E+14 sej/ton

Electricity production: est. using heat to drive mechanical processes;
(est. mean annual temp.in southern Sweden = 12° C):

Carnot ratio = (50%) (Δ T/T); (0.5) [1473° K - (273° K + 12° K)] / 1473° K] = 0.403;

Electricity per ton wood chips = (4.197 MWh heat/ton; Table 15) (0.403) = 1.69 MWhe/ton (3.6E+9 J/Mwh) = 6.08E+9 J/ton

Energy efficiency factor: (6.08E+9 J-electricity / ton) / (2.052E+10 J/ton) = 0.296

Summary of measurements:

ST_4 (5.86E+14 sej/ton) / (6.08E+9 J/ton) = 96,382 sej/J
YR_4 (5.86E+14 sej/ton) / [(1.88 + 2.68)E+14 sej/ton] = 1.29
IR_4 [(1.88 + 2.68)E+14 sej/ton] / (1.31E+14 sej/ton) = 3.48

Figure 27--continued.

(b) Theoretical electricity generation from wood powder:

I Environmental sources: (64.3E+12 sej/ha/yr; Table 16) / (1.008 m^3/ha/yr) (2.35 m^3/ton) = 1.50E+14 sej/ton (includes environmental component of wood powder used in drying)

$F_{1..3}$ Economic inputs to wood chip production = (84.8E+12E+12 sej/ha/yr; Table 15) / (1.008 m^3/ha/yr) (2.35 m^3/ton) = 1.98E+14 sej/ton

(b) Theoretical electricity generation from wood powder (continued):

F_4 Wood powder production: (100.3E+12 sej/ha/yr; Table 16) / (1.008 m^3/ha/yr) (2.35 m^3/ton) = 2.34E+14 sej/ton

F_5 Economic inputs to electric generation:
(est. using district plant operations/maintenance costs + price of wood powder):

a. Price of wood powder delivered at district plant = (1040 SEK/ton) / (6.5 SEK/$, 1988) = 160 $/ton;

Incurred costs of powder production (to avoid double counting of inputs) = silviculture costs (4.90 $ton) + harvest costs (40.60 $/ton) + powder prod. (61.04 $/ton) + delivery costs (11.22 $/ton) = 117.76 $/ton;

Unaccounted cost of wood powder = price - incurred costs = (160.00 - 117.76) $/ton = 42.24 $/ton (1.5E+12 sej/$) = 6.34E+13 sej/ton

b. Operations, maintenance, fuels: (55.9E+12 sej/ha/yr; Table 16) / (1.008 m^3/ha/yr) (2.35 m^3/ton) = 1.303E+14 sej/ton

Economic inputs to electric production = a + b = (0.634 + 1.303)E+12 sej/ton = 1.937E+14 sej/ton

Y_5 $[I + (F_1 + \ldots F_3) + F_4 + F_5]$ = (1.50 + 1.98 + 2.34 + 1.94)E+14 sej/ton = 7.76E+14 sej/ton

Electricity production: est. using heat to drive mechanical processes = (4.795 MWh heat/ton; Table 16) (0.403; Carnot ratio, calculated above) = 1.934 MWhe/ton wood powder (3.6E+9 J/Mwh) = 6.96E+9 J/ton

Energy efficiency factor: (6.96E+9 J-electricity / ton) / (2.052E+10 J/ton) = 0.339

Summary of measurements:

ST_5 (7.66E+14 sej/ton) / (6.96E+9 J/ton) = 111,490 sej/J
YR_5 (7.66E+14 sej/ton) / [(1.98 + 2.34 + 1.94)E+14 sej/ton] = 1.24
IR_5 [(1.98 + 2.34 + 1.94)E+14 sej/ton] / (1.50E+14 sej/ton) = 4.17

investment ratio of wood powder-fueled electricity was higher (4.17 compared to 3.48) producing a lower emergy yield ratio (1.24 compared to 1.29 for wood chips).

It is possible that additional costs associated with electricity generation and plant maintenance would increase the emergy systems requirements and further lower the net emergy yields. It may also be possible to capture an additional 20% of the useful heat of combustion from these wood fuels with stack gas condensation improving the theoretical energy conversion efficiencies and lowering solar transformities (Nilsson personal communication).

A proposed wood-fired electricity plant in Thailand is evaluated in Table 26. Plantation grown eucalyptus supplied at a rate of 220,680 m^3/yr would fuel the plant producing 173.5 GWh/yr of electricity (25 MW operating at 80% capacity). Resource indices are summarized in Figure 28a. An emergy yield ratio of above ground biomass production measured 2.05, comparable to eucalyptus grown in Florida (Figure 14) and willow grown in Sweden (Figure 13). Power generation and plant maintenance (F_3) used the largest amount of economic resources measuring 34% of the total. Economic inputs (F_1, F_2, and F_3) together contributed 49% of the emergy in the electricity. A solar transformity measured 144,850 sej/J. An emergy yield ratio of 2.06 indicates very little net emergy is derived from this proposed method. Because the proposed plants would be small and built near rural communities, transport losses were estimated to be only 3.8% of production.

A rainforest wood-fired electricity plant in Jari, Brazil, evaluated by Odum et al. (1986), is revised and presented here to compare with other electric power alternatives (Table 27). Using 0.61 million tons of mature rainforest logs, 53 MW/yr

Table 26. Emergy evaluation of eucalyptus plantation production, fuelwood development, and wood-fired electricity production at a proposed 25 MW capacity plant in Thailand.[a] Analysis is summarized in Figure 28a.

Note	Item	Resource units/MWhe (J, $)	Solar emergy per unit[b]	Solar emergy per MWH electr. (E+12 sej/MWhe)
I	Envrionmental sources:			
	1. Evapo-transpired rain	2.55E+09 J	18200	46.40
F_1	Plantation management:			
	2. Fertilizer	1.40E+03 g	4.80E+09	6.72
	3. Human labor	1.91 $	3.69E+12	7.04
	4. Capital costs	8.29 $	3.69E+12	30.60
Y_1	Above ground production	7.01E+09 J	ST_1	90.70
F_2	Harvest and transport:			
	5. Felling and conversion	1.27 $	3.69E+12	4.69
	6. Diesel fuel	9.60E+07 J	47900	4.60
	7. Electricity for chipper	3.21E+07 J	70500	4.60
	8. Transport cost	4.38$	3.69E+12	16.10
	9. Road maintenance	0.20 $	3.69E+12	0.75
	10. Administration	0.85 $	3.69E+12	3.13
Y_2	Harvested biomass	6.66E+09 J	ST_2	124.63
F_3	Power generation			
	11. Operations costs	26.16 $	3.69E+12	96.50
	12. Capital costs, interest	22.20 $	3.69E+12	81.90
Y_3	Electricity generation (1 MWh)	3.60E+09 J	ST_3	523.40
	13. Transmission losses	11.20 $	3.69E+12	41.30
Y_4	Electricity delivered to user	3.46E+09 J	ST_4	564.79

Summary of measurements:

Solar transformity:

ST_1	Above ground production	12,952	sej/J
ST_2	Harvested biomass	18,369	sej/J
ST_3	Electricity generation	145,390	sej/J
ST_4	Electricity delivered to user	163,240	sej/J

Table 26--continued.

Emergy yield ratio:		
YR_1	Above ground production	2.05
YR_2	Harvested biomass	1.59
YR_1	Electricity generation	2.06
YR_2	Electricity delivered to user	1.89
Emergy investment ratio:		
IR_1	Above ground production	0.96
IR_2	Harvested biomass	1.69
IR_1	Electricity generation	0.95
IR_2	Electricity delivered to user	1.12

Notes.

a. Analysis based on a proposed 25 MW power plant operating at an 80% loading factor (173.5 GWhe) using 220,680 m^3 fuelwood produced from a 7356 ha plantation of *Eucalyptus camaldulensis* yielding on average 30 m^3/ha/yr for 5.75 year rotations. Data from the Dendro Thermal Power Programme of Thailand (NEA/FEP 1990) unless cited otherwise in footnotes.

b. Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej*/J); inputs reported as mass use *sej*/g; monetary inputs use *sej*/$ for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

1. Evapotranspired rain: (7356 ha, fuelwood plantation area) / (173.5 GWh-electricity generated/yr) = 0.042 ha/MWhe (10,000 m^2/ha) (1.56 m/yr, rainfall) (78% ET; est. from Table 9) (1000 kg/m^3) (4940 J/kg) = 2.55E+9 J/MWhe (5.75 yr. rotation; est. for sustainable harvest) = 1.47E+10 J/MWhe

2. Fertilizer: (1.1E+03 g/m^3 wood) (1.272 m^3/MWhe; fuelwood used, Y_1 below) (1.40E+03 g/MWhe)

3. Plantation labor: (38 Baht/m^3) (1.272 m^3/MWhe) / (25 Baht/$, 1987) = 1.91 $/MWhe

Y_1 Above ground production: (30 m^3/ha/yr) (7356 ha) = 220,680 m^3/yr / (173.5 GWh-electricity; 80% of 25 MW/yr) = 1.272 m^3/MWhe (0.34 tons/m^3; est. wood density for *E. deglupta*, Reyes et al. 1992) (1.62E+04 J/g; est using energy content of Salix spp.) = 7.01E+09 J-wood/MWhe

5. Felling and fuelwood conversion (chipping): (25 Baht/m^3) (1.272 m^3/MWhe; Y_1 above) / (25 Baht/$, 1987) = 1.27 $/MWhe

6. Fuel (est. from salix plantation, Table 8): (harvesting, 1.98 liters/m^3 + 0.14 l/m^3) = 2.12 l/m^3 (9.89 kWh/liter) (3.6E+06 J/kWh) (1.272 m^3/MWhe, Y_1 above) = 9.60E+07 J/MWhe

7. Electricity used in chipper: (7 kWh/m^3) (1.272 m^3/MWhe; Y_1 above) (3.6E+06 J/kWh) = 3.21E+07 J/MWhe

   Note: A solar transformity for services supporting electricity used in wood chipping is estimated as follows: (ST_3) / (YR_3) = (144,850 sej/J) / (2.06) = 70,500 sej/J.

8. Transport costs: (86 Baht/m^3) (1.272 m^3/MWhe; Y_1 above) / (25 Baht/$, 1987) = 4.38 $/MWhe

Table 26--continued.

9. Road costs: (4 Baht/m^3) (1.272 m^3/MWhe; Y_1 above) / (25 Baht/\$, 1987) = 0.20 \$/MWhe

10. Administrative, overhead, profit/risk: 15% harvest and transport cost; (0.15) (5.65 \$/MWhe) = 0.85 \$/MWhe

Y_2 Harvested biomass: 209,770 m^3 fuelwood/yr for 25 MW plant operating at 80% load factor; (209,770 m^3) / (173.5 GWhe/yr) = 1.209 m^3/MWhe (0.34 tons/m^3) (1.62E+04 J/g) = 6.66E+09 J/MWhe

11. Fuel, operation costs: (0.65 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 26.16 \$/MWhe

12. Capital costs @ 8% interest: (0.56 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 22.20 \$/MWhe

Y_3 Electricity generation: (1 MWhe) (3.60E+09 J/MWh) = 3.60E+09 J

13. Transmission costs: \$ cost per kWh electricity delivered is based on distance from proposed power plant to rural substation; (0.28 Baht/kWh) / (25 Baht/\$, 1987) (1000 MWh/kWh) = 11.20 \$/MWhe

Y_4 Electricity delivered to user: 3.8% transmission losses; (0.038) (3.6E+6 J; Y_3 above) = 3.46E+09 J

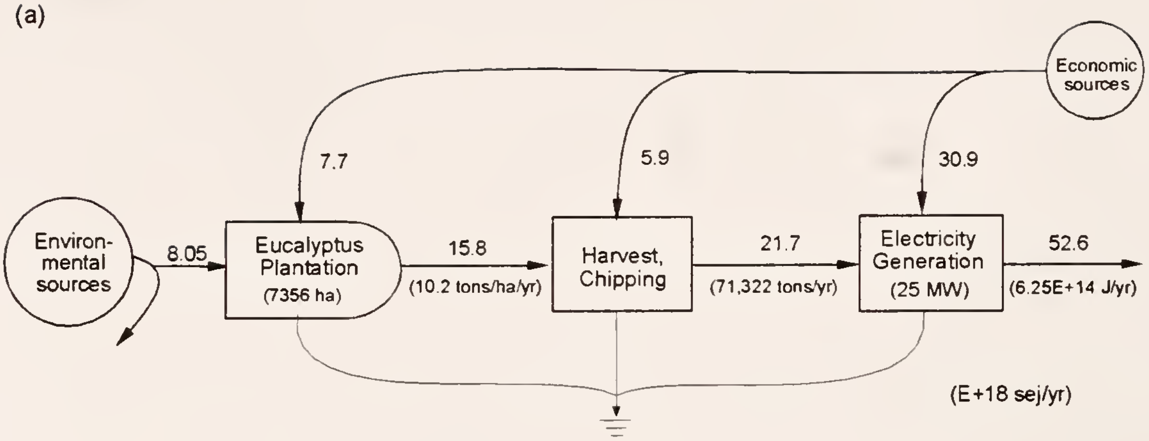
Summary of measurements:
I_1 Environmental sources supporting annual production = item 1 = 4.64E+13 sej/yr
F_1 Plantation management = items 2-4 = 4.44E+13 sej/MWhe
F_2 Harvesting, chipping, transport = items 5-10 = 3.39E+13 sej/MWhe
I_3 Total environ. sources over 5.75 year rotation = I_1 (5.75 years) = 2.67E+14 sej/MWe
F_3 Electricity = items 11-12 = 1.78E+14 sej/MWhe
F_4 Transmission costs = item 13 = 4.13E+13 sej/MWhe
Y_1 $I_1 + F_1$ = 90.7E+12 sej/yr
Y_2 $I_1 + F_1 + F_2$ = 124.6E+12 sej/yr
Y_3 $I_3 + F_1 + F_2 + F_3$ = 523.4E+12 sej/yr
Y_4 $I_3 + F_1 + \ldots F_4$ = 564.8E+12 sej/yr

Solar transformity = Y_i (sej/MWhe) / Y_i (J/MWhe)
ST_1 Above ground production = (9.07E+13 sej/MWhe) / (7.01+9 J/MWhe) = 12,952 sej/J
ST_2 Harvested biomass = (1.22E+14 sej/MWhe) / (6.66E+9 J/MWhe) = 18,369 sej/J
ST_3 Electricity = (523.4E+14 sej/MWhe) / (3.60E+09 J/MWhe) = 145,390 sej/J
ST_4 Electricity delivered to user = (564.8E+14 sej/MWhe) / (3.46E+09 J/MWhe) = 163,240 sej/J

Emergy yield ratio = Y_i / ($F_1 + \ldots F_i$):
YR_1 (90.7E+12 sej/MWhe) / (44.4E+12 sej/MWhe) = 2.05
YR_2 (124.6E+12 sej/MWhe) / (44.4 + 33.9)E+12 sej/MWhe = 1.59
YR_3 (523.4E+12 sej/MWhe) / (44.4 + 33.9 + 178.4)E+12 sej/MWhe = 2.06
YR_4 (564.8E+12 sej/MWhe) / (44.4 + 33.9 + 178.4 + 41.3)E+12 sej/MWhe = 1.89

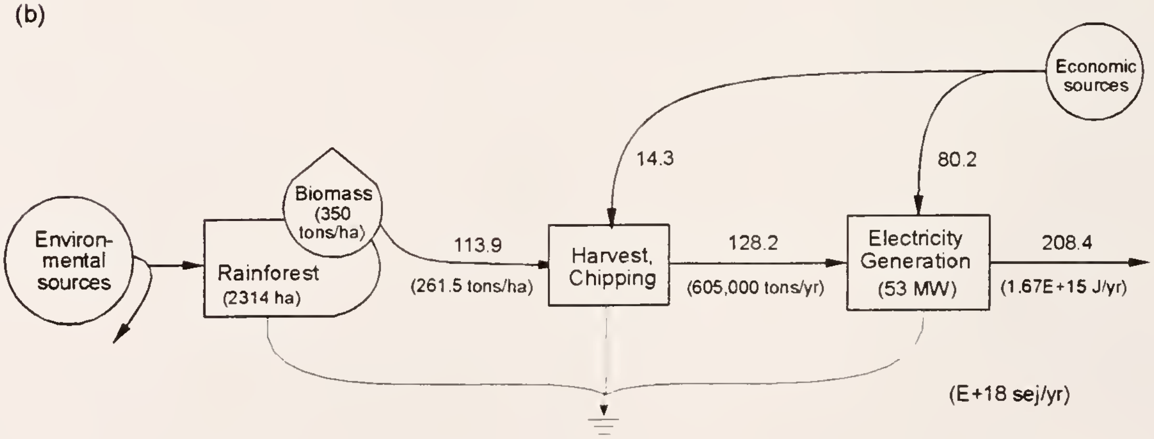
Emergy investment ratio = ($F_1 + \ldots F_i$) / (I):
IR_1 (44.4)E+12 sej/MWhe / (46.4E+12 sej/MWhe) = 0.96
IR_2 (44.4 + 33.9)E+12 sej/MWhe / (46.4E+12 sej/MWhe) = 1.69
IR_3 (44.4 + 33.9 + 178.4)E+12 sej/MWhe / (266.9E+12 sej/MWhe) = 0.95
IR_4 (44.4 + 33.9 + 178.4 + 41.3)E+12 sej/MWhe / (266.9E+12 sej/MWhe) = 1.12

(a)



	Above ground production	Fuelwood	Electricity
Solar transformity	12,952 sej/J	18,369 sej/J	145,390 sej/J
Emergy yield ratio	2.05	1.59	2.06
Emergy investment ratio	0.96	1.69	0.95

(b)



	Above ground biomass	Fuelwood	Electricity
Solar transformity	14,264 sej/J	21,617 sej/J	166,470 sej/J
Emergy yield ratio	—	8.97	2.21
Emergy investment ratio	—	0.12	0.83

Figure 28. Systems diagrams of wood-fired electricity production: (a) proposed 25 MW capacity plant in Thailand (Table 26); (b) 53 MW plant in Jari, Brazil (revised from Odum et al. 1986; Table 27).

Table 27. Emergy evaluation of wood-fired electricity production in Jari, Brazil.[a] Analysis is summarized in Figure 28b.

Note	Item	Resource units/yr (J, $)	Solar emergy per unit[b]	Solar emergy flow (E+18 sej/yr)
1.	Evapotranspiration	6.26E+15 J	18200	113.91
Q_1	Above ground biomass	7.99E+15 J	ST_1	113.91
2.	Fuel used in harvest	1.29E+14 J	47900	6.19
3.	Electricity for chipping	5.89E+13 J	56500	3.33
4.	Human services	690,000 $	6.9E+12	4.76
Y_2	Harvested fuelwood	5.97E+15 J	ST_2	128.19
5.	Generator plant operations	4.18E+14 J	192,000	80.23
Y_3	Electricity generation	1.67E+15 J	ST_3	208.42

Summary of measurements:

Solar transformity:

ST_1	Above ground biomass	14,264 sej/J
ST_2	Harvested fuelwood	21,617 sej/J
ST_3	Electricity	166,470 sej/J

Emergy yield ratio:

YR_2	Harvested fuelwood	8.97
YR_3	Electricity	2.21

Emergy investment ratio:

IR_2	Harvested fuelwood	0.12
IR_3	Electricity	0.83

Notes.

[a] Revised from Odum et al. 1986; based on initial clearcutting of 2314 ha, 300 year old (est.) forest, harvesting 6.05E+5 tons rainforest logs (261.5 tons/ha), and generating 53 MW electricity. Subsequent plantings planned on 100 year rotations.

[b] Inputs calculated as available energy are converted to solar emergy using solar transformities (*sej/J*); monetary inputs use *sej/$* for regional economy and year of operation (Table 2 unless cited otherwise in footnotes).

Table 27--continued

1. Evapotranspiration: (3 mm/day; ET) (365 d/yr) / (1000 mm/m) (1E+4 m^2/ha) (1E+6 g/m^3; H_20 wt.) (4.94 J/g; Gibbs free energy) (2314 ha) (100; area multiplier for sustainable harvest) (0.5, est. of energy used up) = 6.26E+15 J/rotation/53 MWe

Q_1 Above ground biomass: (350 tons/ha) (9.86E+9 J/ton) (2314 ha) = 7.99E+15 J

2. Fuels used in harvest (est. from monterrey pine plantation; Odum and Odum 1983): (5.20E+7 J/m^3, logging + 3.30E+7 J/m^3, loading + 1.30E+8 J/m^3, transport) = 2.15E+8 J/m^3 (261.5 m^3/yr, harvest) (2300 ha plantation) = 1.29E+14 J/yr

3. Electricity used in debarking, chipping: 9.80E+7 J/m^3 (261.5 m^3/yr, harvest) (2300 ha plantation) = 5.89E+13 J/yr

   Solar transformity for electricity used in chipper was estimated for societal inputs as follows: (ST_3/YR_3) = (192,000 sej/J) / (3.40) = 56,500 sej/J

4. Human services: 300 \$/ha/yr (2300 ha) = 690,000 \$/yr

Y_2 Fuelwood harvested = 6.05E+5 tons per 53 MW electricity produced; Y_3 below: (6.05E+5 tons) / (2314 ha) = 261.5 tons/ha; (6.05E+5 tons) (9.86E+9 J/ton) = 5.97E+15 J/yr

5. Generator plant operations, maintenance: assume 25% feedback of electric output: (1.67E+15 J/yr; Y_3 below) (0.25) = 4.18E+14 J/yr; Solar transformity = ST_3 as calculated below.

Y_3 Electricity generated = 53 MW/yr: (5.30E+7 W/yr) (1 J/W*sec) (3.15E+7 sec/yr) = 1.67E+15 J/yr - electricity used (4.18E+14 J/yr; item 5 above) = 1.25E+15 J/yr

Solar transformity:
ST_1 Above ground biomass = (113.91E+18 sej/yr) / (7.99E+15 J/yr) = 14,264 sej/J
ST_2 Harvested fuelwood = (128.19E+18 sej/yr) / (5.97E+15 J/yr) = 21,617 sej/J
ST_3 Electricity = (208.42E+18 sej/yr) / (1.25E+15 J/yr) = 166,470 sej/J

Emergy yield ratio:
YR_2 Y_1 / (items 2+... 4) = (128.19E+18 sej/yr) / (14.28E+18 sej/yr) = 8.97
YR_3 Y_2 / (items 2+... 5) = (208.42E+18 sej/yr) / (14.28 + 80.23)E+18 sej/yr = 2.21

Emergy investment ratio:
IR_2 (items 2+... 4) / (item 1) = (14.28E+18 sej/yr) / (113.91E+18 sej/yr) = 0.12
IR_3 (items 2+... 5) / (item 1) = (14.28 + 80.23)E+12 sej/yr / (113.91E+18 sej/yr) = 0.83

of electricity was generated. Economic sources accounted for 29% of emergy yield; rainforest emergy supplied 71% (Figure 28b). The emergy yield ratio measured 3.40, comparable to other fossil fuel-based operations in Thailand (Figure 26) but less than electricity produced in Gainesville using natural gas or coal (Figure 25). A transformity for electricity from rainforest wood measured 1.67E+5 sej/J. The Jari site plans to replant native forests cut for fuelwood and resume cutting on 100 year rotations. Whether this rotation will sustainably produce the required volume of fuelwood or high enough temperatures to generate electric power is not known. The relationship between time, space and energy is further explored in the discussion section of this study.

DISCUSSION

In this chapter, data and indices from the analyses are synthesized and graphed to test postulates and articulate policy initiatives addressed in this dissertation. Production yields are related to inputs for all agroforest systems evaluated and biophysical limits to biomass production are identified from observed minimum transformities. Temporal limits to biomass production are considered by relating net yields to rotation periods. The role of economic investments in the delivery of primary fuels and the resultant declines in net yield are addressed. Limits to biomass production are considered by comparing analyses of wood-fired electricity to those made of electricity produced from fossil-carbon fuels. Overview comparisons of 3 possible woodfuel alternatives are made which summarize relationships of energy yield, quality, net emergy, and investments to requirements of time and area. Simulation results of computer minimodels are then presented to test theories and verify data analyses. A synthesis of the findings are listed and implications of biomass limits to global environmental-energy policy are discussed.

Comparison of Forest Production Systems

A summary of emergy measurements and indices for agroforest production systems evaluated in this study is given in Table 28. This table is ordered by

Table 28. Summary of measurements calculated for evaluated agroforest ecosystems.

Note	Forest type	Location	Rotation age (yrs)	Solar transformity (sej/J)		Emergy yield ratio (YR)		Investment ratio (IR)	
				Forest production	Harvested biomass	Forest production	Harvested biomass	Forest production	Harvested biomass
1.	Willow plantation	Sweden	4.5	4850	6,720	1.49	1.33	2.05	3.02
2.	Fuelwood plantation	Florida	5	11,270	16,143	1.61	1.38	1.65	2.61
3.	Eucalyptus plantation	Thailand	5.8	12,952	18,369	2.05	1.61	0.96	1.64
4.	Siris plantation	Puerto Rico	11	8,344	11,335	3.15	2.32	0.46	0.76
5.	Southern slash pine	Florida	25	5829	21,563	8.86	2.82	0.13	0.55
6.	Tropical palm forest	Puerto Rico	27	2343	---	---	---	---	---
7.	Temperate loblolly pine	Illinois	30	4075	11,043	6.74	2.57	0.17	0.64
8.	Guanica tropical dry forest	Puerto Rico	47	5624	---	---	---	---	---
9.	Tropical lowland tabonuco	Puerto Rico	59	9000	---	---	---	---	---
10.	Temperate mixed hardwoods	Illinois	60	9834	19,697	11.03	3.95	0.10	0.34
11.	Tropical premontane colorado	Puerto Rico	62	5864	---	---	---	---	---
12.	Managed spruce/pine	Sweden	80	4928	10,083	12.39	2.51	0.09	0.66
13.	Temperate mixed hardwoods	Illinois	80	10,399	18,383	11.64	3.84	0.09	0.35
14.	Temperate loblolly pine	Illinois	90	5863	10,272	9.68	2.66	0.12	0.60
15.	Northern mixed coniferous	Sweden	100	7188	14,243	---	4.09	---	0.32
16.	Temperate mixed hardwoods	Illinois	120	11,740	20,645	12.81	4.24	0.08	0.31
17.	Tropical lowland rainforest	Papua New Guinea	140	18,533	33,117	---	2.27	---	0.79
18.	Tropical cloud forest	Puerto Rico	172	2322	---	---	---	---	---
19.	Old growth spruce	Sweden	200	9200	18,778	---	5.41	---	0.23
20.	Tropical lowland rainforest	Brazil	300	14,264	21,617	---	8.97	---	0.83

Calculations given as footnotes to evaluation tables.

Table 28--continued.

Note	Forest type	Solar empower production (E+12 sej/ha/yr)	Solar emergy biomass (E+12 sej/ha)	(F1) Silviculture (E+12 sej/ton)	(F2) Harvest (E+12 sej/ton)	Forest production (sej/J)		Harvested biomass (sej/J)	
						Environmental sources	Economic sources	Environmental sources	Economic sources
1.	Willow plantation	1087.6	4,540	63.5	71.1	1595	3255	1667	5053
2.	Fuelwood plantation	2455.1	12,266	117.2	136.7	4270	7000	4445	11698
3.	Eucalyptus plantation	2140.2	12,734	102.4	130.3	6634	6318	6960	11409
4.	Siris plantation	1452.7	11,523	44.3	60.2	5695	2649	6449	4886
5.	Southern slash pine	1054.5	17,330	12.4	38.9	5171	658	13917	7646
6.	Tropical palm forest	745.9	7,616	---	---	2343	0	---	---
7.	Temperate loblolly pine	720.0	21,607	12.1	31.7	3470	605	6746	4297
8.	Guanica tropical dry forest	649.8	4,238	---	---	5624	0	---	---
9.	Tropical lowland tabonuco	1582.3	29,823	---	---	9000	0	---	---
10.	Temperate mixed hardwoods	675.1	40,469	16.2	45.3	8942	892	14710	4987
11.	Tropical premontane colorado	746.2	13,334	---	---	5864	0	---	---
12.	Managed spruce/pine	386.3	10,315	8.2	40.3	4530	398	6066	4017
13.	Temperate mixed hardwoods	672.2	53,777	16.3	49.3	9506	893	13596	4787
14.	Temperate loblolly pine	683.9	61,589	12.1	44.1	5257	606	6410	3862
15.	Northern mixed coniferous	470.1	17,740	---	36.1	7188	0	10761	3482
16.	Temperate mixed hardwoods	667.0	79,952	16.7	50.4	10824	916	15776	4869
17.	Tropical lowland rainforest	10828.2	140,915	---	163.4	18533	0	18528	14589
18.	Tropical cloud forest	143.9	3,223	---	---	2322	0	---	---
19.	Old growth spruce	226.5	35,491	---	34.9	9200	0	15307	3471
20.	Tropical lowland rainforest	5300.1	99,893	---	31.8	14264	0	19207	2410

Data for calculations are given in evaluation tables.

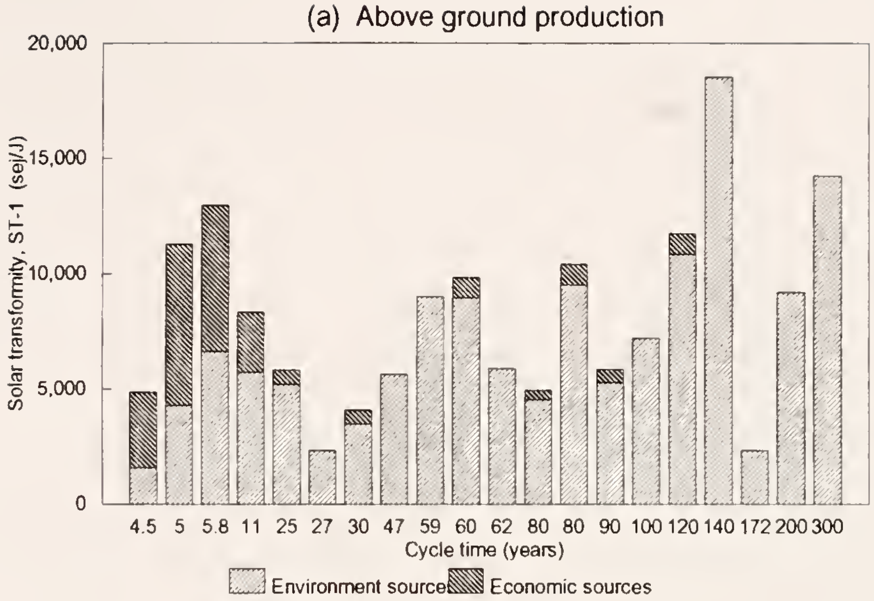
increasing cycle time to facilitate comparisons, following the format in Table 3 of the Introduction section. Transformities and indices of yield and investment are reported for forest production and harvested biomass. Annual empower and emergy stored in above ground biomass are also synthesized from the analyses along with silvicultural and harvest investments reported per ton of biomass yield. These measures are compared and related to each other in the following paragraphs through graphical analysis and inference to draw conclusions regarding forest processes and limits to biomass production.

Solar Transformities of Agroforest Systems

Natural systems, including tropical ecosystems of Puerto Rico, generally had lower transformities for production than intensively managed forests and plantations. Production transformities did not increase with forest age in all cases. Solar transformities for production (ST_1) and harvested biomass (ST_2) are divided into environmental and economic sources in Figure 29. Economic sources contributed an increasingly smaller percentage of total inputs to production with increasing rotation age (Figure 29a). This trend is carried over to harvested biomass (Figure 29b) although the economic contributions per ton harvested biomass were of similar magnitude across forest ages, and lower for some intensively managed systems.

Emergy Yield Ratio as a Function of Economic Feedback

Economic feedback to harvest intensively managed systems, although a larger percentage of total emergy inputs relative to environmental sources, was often lower



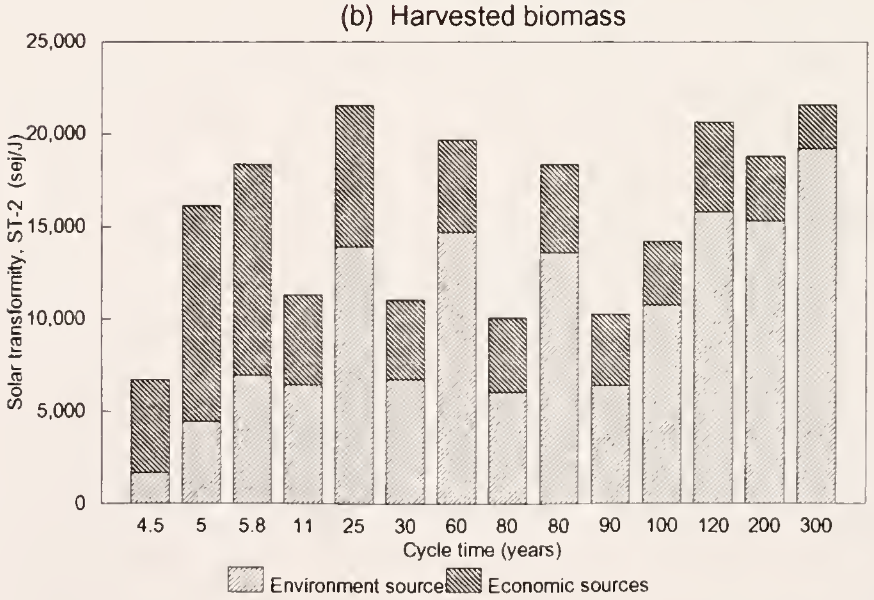


Figure 29. Environmental and economic components of solar transformities for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass, rank ordered by cycle time.

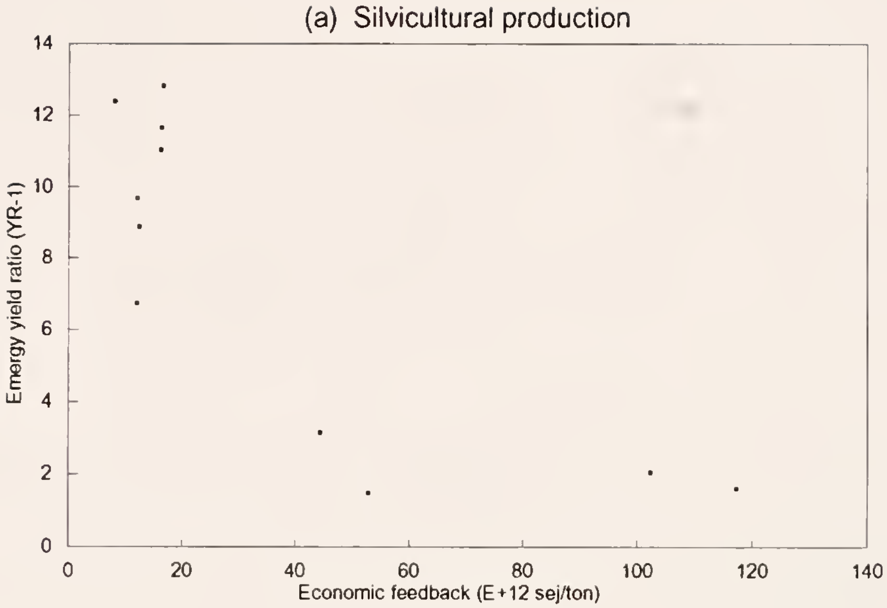
per unit harvested biomass than in older and unmanaged systems (Table 28). This may be a reflection of management efforts to order and simplify production facilitating removal. Emergy yield ratio of production and harvested biomass is shown to decrease rapidly with increases in economic feedback (Figure 30) with some system investments drawing down emergy yields close to unity. An inflection point is identified at about 30E+12 sej/ton in Figure 30a with systems producing little or no net yield with silvicultural investments above this input level. Increasingly greater net yield ratios were achieved with small reductions in economic inputs below this level.

Optimal Investments for Production and Harvest of Biomass

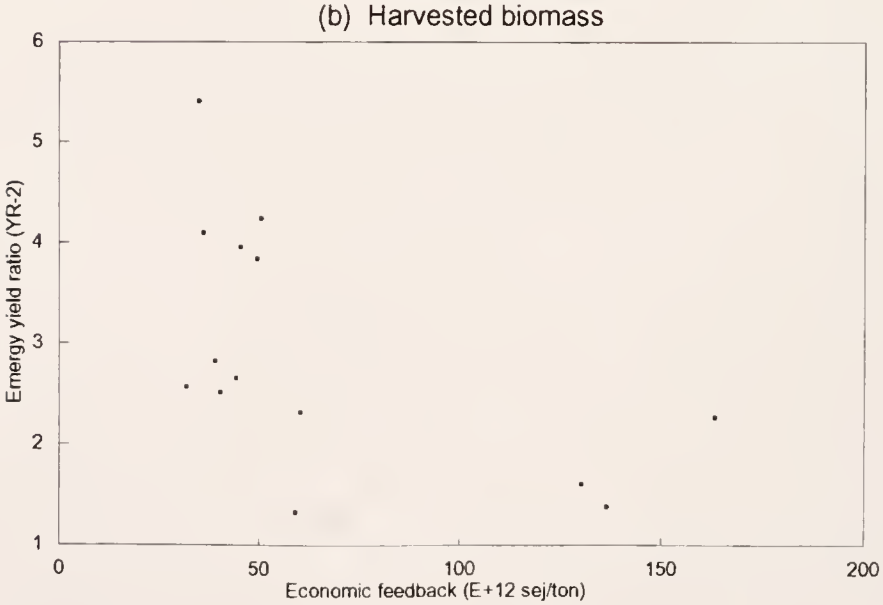
Transformities, in general, increased as a function of emergy investment ratio (Figure 31). Some intensively managed production systems with high investment ratios had lower transformities. This may be a reflection of management subsidies improving the efficiency of production by controlling competition and reducing stress. These efforts increase inputs of economic emergy and result in lower net emergy yields. Optimal production would lower both the emergy investment ratio and the solar transformity, moving production toward the lower left portion of the graph.

Thermodynamic Minimum Transformities for Biomass

Transformities for managed forest production were not measured below 4,000 sej/J (Figure 31a). For managed systems, conifer production measured between 4,000-5,000 sej/J. Managed temperate hardwood production ranged from 9,000-11,700 sej/J increasing with rotation age. The lowest observed transformity for above ground



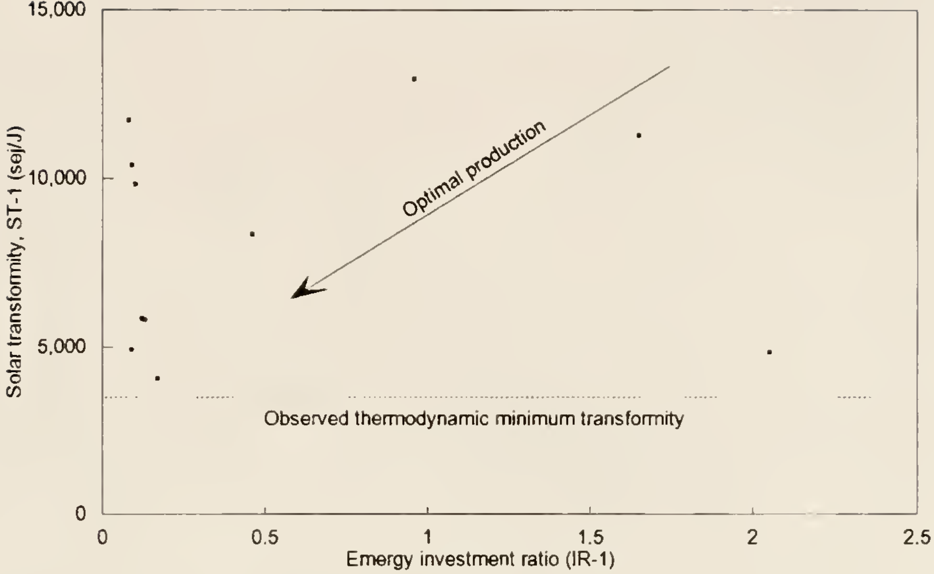
(a) Silvicultural production



(b) Harvested biomass

Figure 30. Emergy yield ratio as a function of economic feedback for evaluated agro-forest ecosystems: (a) silvicultural forest production; and (b) harvested biomass.

(a) Above ground production



(b) Harvested biomass

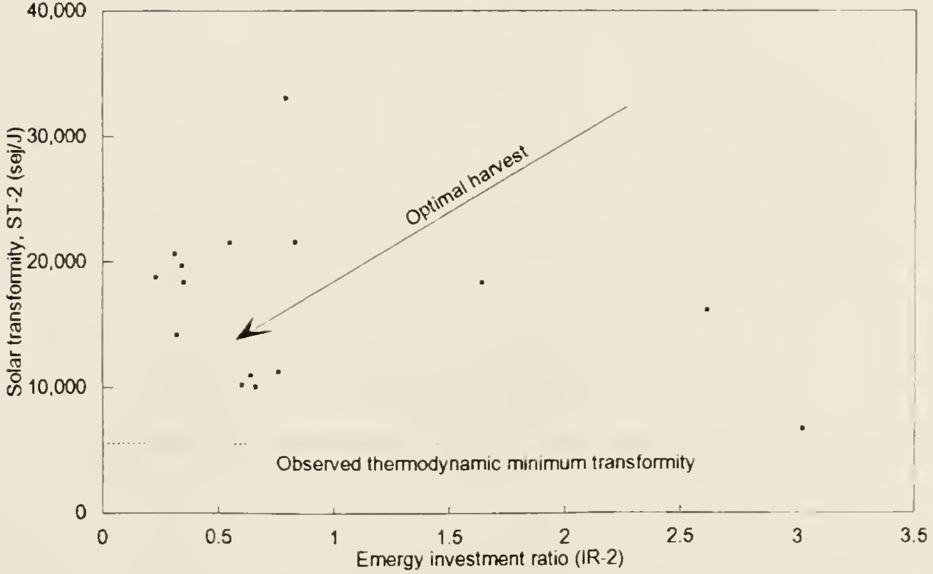


Figure 31. Solar transformity as a function of emergy investment ratio for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass.

production in natural systems measured 2300 sej/J for both cloud forests and palm forests in Puerto Rico. These observations suggest a possible lower emergy limit to biomass production due to factors including photosynthesis conversion efficiencies and availability of flow-limited environmental energy sources. Similarly, transformities for harvested biomass were generally measured above 10,000 sej/J -- the exception being harvested willow from short-rotations in Sweden which measured 6720 sej/J.

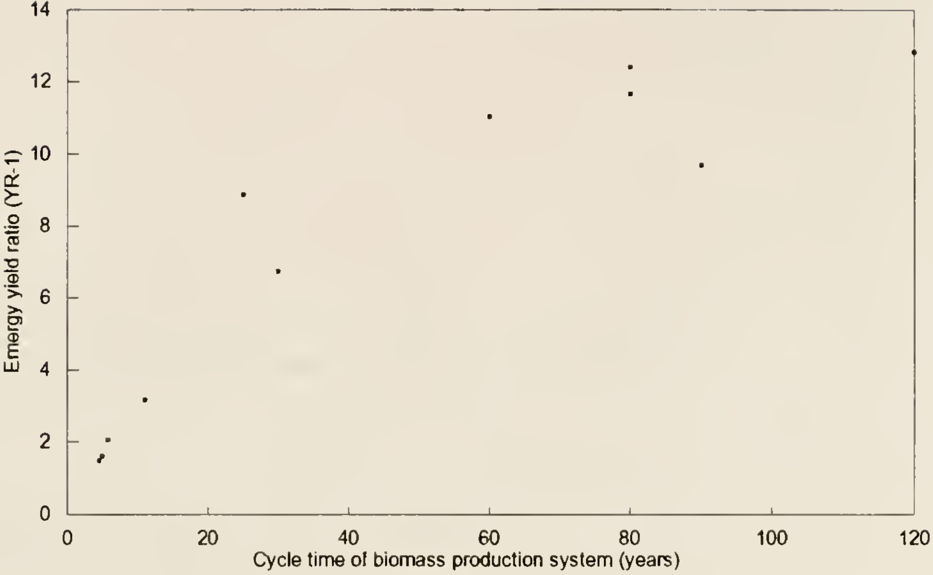
Thermodynamic conversion limits for biomass may be a measure of system efficiency. Increased management efforts, technological advances and economic subsidies may act to increase biomass production efficiencies (i.e., lowering solar transformities), but the economic emergy costs are high, reducing net contributions to the receiving economy.

Emergy Yield and Investment as Functions of Cycle Time

The role of forest age or cycle time related to the net yield of agroforest delivery systems is shown in Figure 32 for biomass production and harvest. As the frequency of harvest increases, the net emergy yield relative to economic source inputs decreases. Older, natural systems and unmanaged forests deliver greater net emergy yields than intensively managed ones, yet these yields are time dependent because the environmental sources used in production are flow limited. Yield ratio as a function of cycle time for harvested biomass (Figure 32b) shows a strong correlation ($r^2 = 0.9$).

A diminishing slope for above ground biomass yield (Figure 32a) as a function of cycle time indicates a limiting factor, curvilinear relationship with limits to net yield. Decreasing slopes for both correlations reflect lower emergy yield ratios with

(a) Above ground production



(b) Harvested biomass

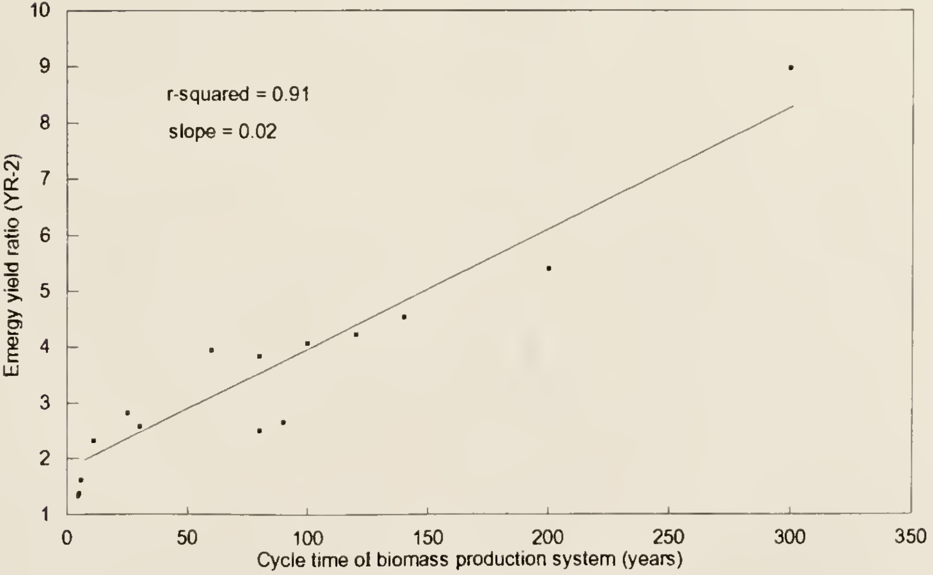


Figure 32. Emergy yield ratio as a function of cycle time for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass.

increased processing. Management and economic feedbacks which reduce rotation periods of production systems increase investments and lower net yields.

The emergy investment ratio is shown to increase rapidly as rotation periods are reduced (Figure 33). Increasing cycle periods above an inflection point located at about 20 years results in investment ratios below unity with systems receiving as much or more resources from the environment than from economic sources. To shorten rotation periods below this time interval, investment ratios increase rapidly with correspondingly smaller reductions in cycle time.

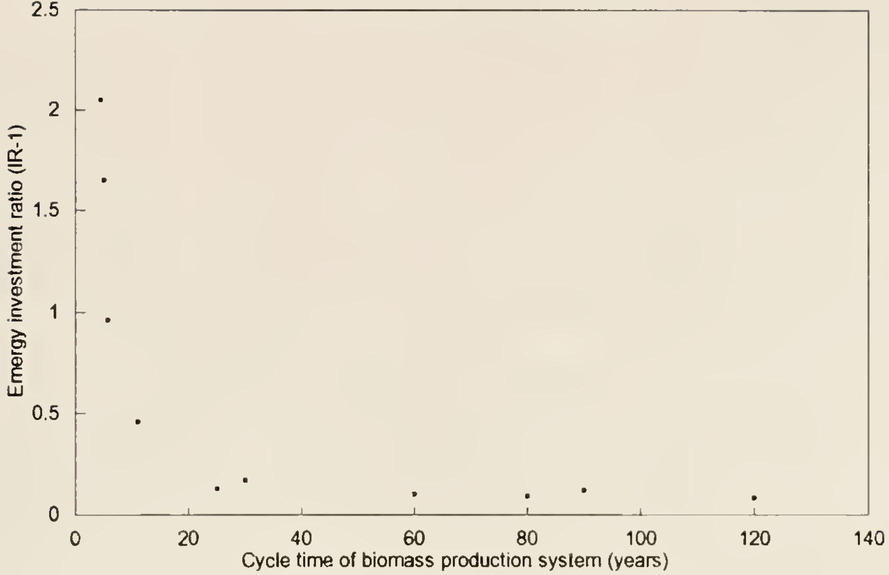
Comparison of Electric Power Transformations

Table 29 summarizes measurements calculated for electricity evaluations undertaken in this dissertation. Transformities and indices of yield and investment are reported for electricity and primary fuel sources if analyzed in evaluations. Economic feedback per MWh electric output, calculated from evaluation tables, is also given for overview and comparison between generation options. Relationships between fuel sources, investments, and electric yields are investigated next using this data synthesis.

Solar Transformities for Primary Fuels and Electricity

Transformities for primary fuels were higher for nonrenewable sources of natural gas and coal than for wood-based fuels. Transformities for primary fuels ranged from 15,000 sej/J for wood chips to 40,000 for natural gas delivered. Electricity transformities ranged from just below 100,000 sej/J to almost 200,000 sej/J,

(a) Above ground production



(b) Harvested biomass

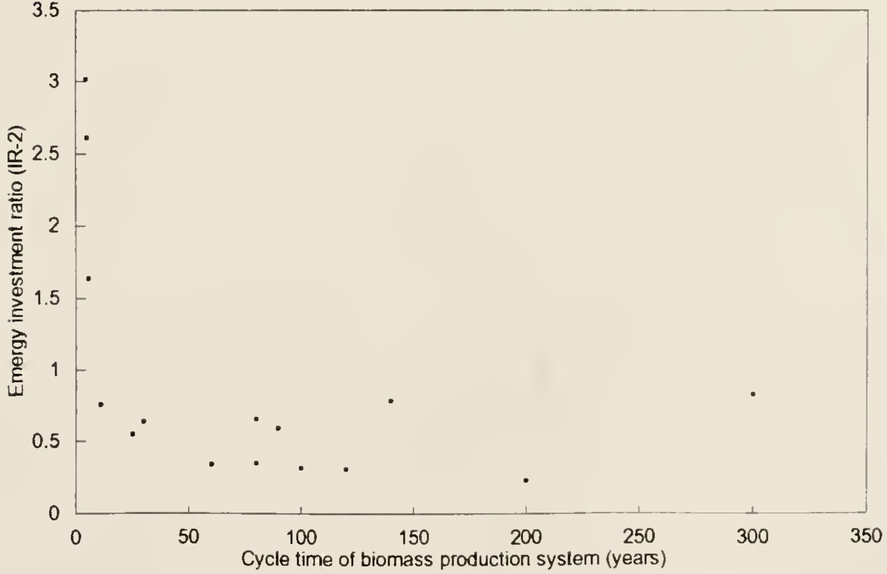


Figure 33. Emergy investment ratio as a function of cycle time for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass.

Table 29. Summary of measurements calculated from evaluations of electricity generation.

Note	Primary fuel type	Location	Energy efficiency factor	Solar transformity (sej/J)		Emergy yield ratio (YR)		Investment ratio (IR)		Emergy feedback / electric output (E+12 sej/MWhe)
				Primary fuel	Electricity	Primary fuel	Electricity	Primary fuel	Electricity	
1.	Natural gas	Gainesville, K-7	0.282	39,936	192,498	9.53	3.81	0.12	0.36	181.98
2.	Natural gas	Gainesville, K-8	0.282	34,841	168,335	9.13	4.44	0.12	0.29	136.32
3.	Natural gas	Gainesville, DH-1	0.282	39,255	151,604	9.09	5.43	0.12	0.23	100.52
5.	Natural gas	Thailand	0.282	---	164,927	---	3.94	---	0.34	150.55
4.	Coal	Gainesville, DH-2	0.324	31,830	107,736	11.63	6.02	0.09	0.20	64.46
6.	Coal	Thailand	0.360	---	126,886	---	2.74	---	0.58	166.78
7.	Oil	Thailand	0.380	---	153,349	---	3.22	---	0.45	171.21
8.	Lignite	Thailand	0.364	---	152,757	---	3.09	---	0.48	177.86
9.	Wood chips	Thailand (proposed)	0.514	18,369	145,390	1.59	2.05	1.69	0.96	259.20
10.	Wood chips	Jari, Brazil	0.209	21,617	166,470	8.97	2.21	0.12	0.83	272.19
11.	Wood chips	Sweden (theoretical)	0.296	15,557	96,382	1.70	1.29	1.44	3.48	269.53
12.	Wood powder	Sweden (theoretical)	0.339	29,844	111,490	1.35	1.24	2.88	4.17	324.25

Calculations given as footnotes to evaluation tables.

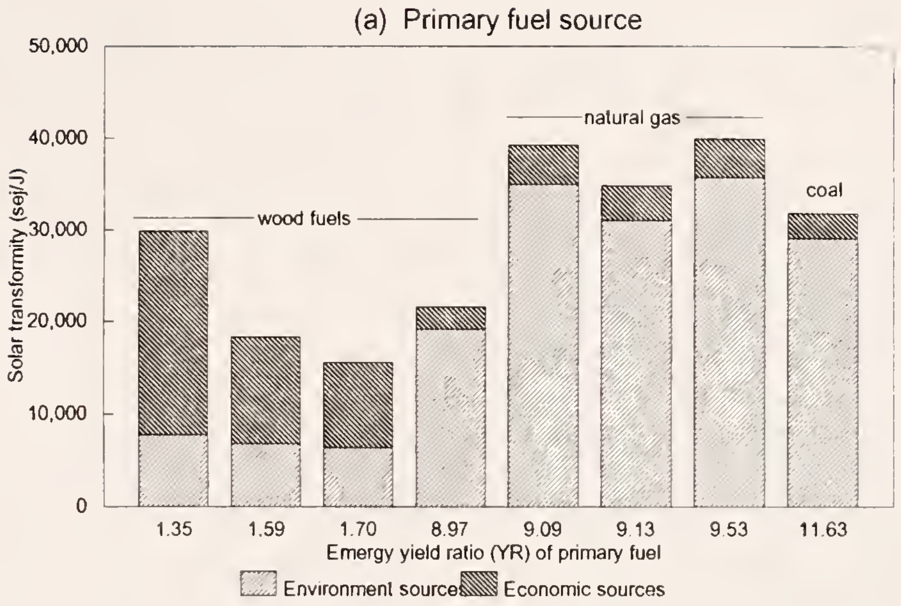
lower generally for wood-fired electric sources than for electricity from nonrenewable sources.

Although transformities were generally higher for electricity generated from non-renewable fuels than from wood fuels, emergy yield ratios were higher (Figure 34). This was due to the greater contribution of environmental and geologic sources in fossil carbon-based fuels. It is possible that the analyses of wood-fired systems are not complete and because they are either proposed or possible systems, are not yet adequately tested to account for all inputs. The transformity for electricity at the Jari, Brazil plant, the only operating wood-fired system, was the highest for all wood-fired evaluations and within the range of other existing operations.

A greater percentage of emergy was derived from economic sources for wood-fired systems than for electricity generation from nonrenewable sources. Economic components of wood fuels averaged 52% of the transformation emergy compared with an average of 10% for nonrenewable fuels (Figure 34a). Wood-fired electricity derived on average 63% of the emergy used from economic sources; 26% of emergy used in electricity generated from fossil carbon sources was invested from economic sources (Figure 34b).

Emergy Yield Ratio as a Function of Economic Feedback

Emergy from economic sources averaged twice as high for wood-fired electricity (mean = 281E+12 sej/MWh) than for electricity from fossil carbon sources (mean = 144E+12 sej/MWh). Electricity generated from coal required the least



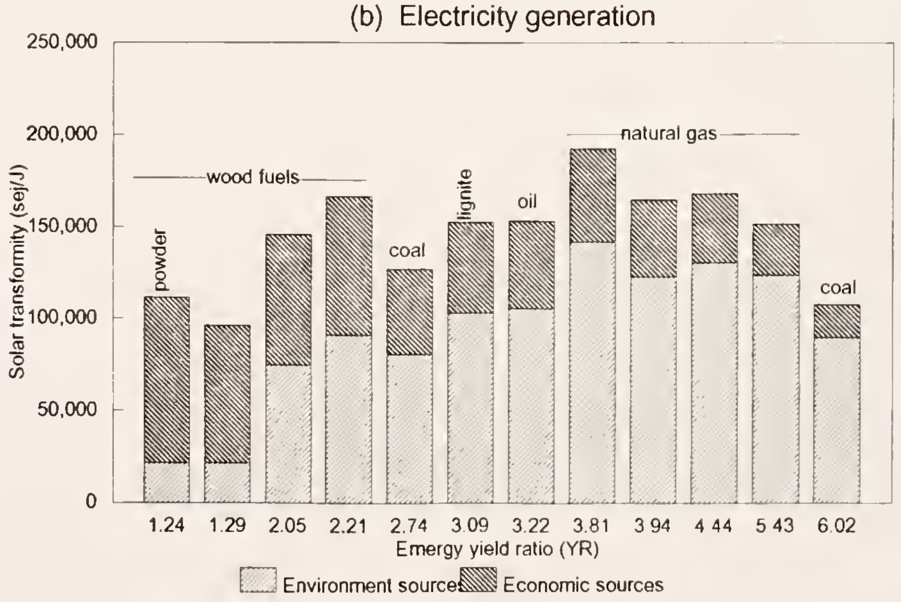


Figure 34. Environmental and economic components of solar transformities for evaluated systems of electricity generation: (a) primary fuel source; and (b) electricity.

investment from economic sources with smaller investments per unit output for larger plant capacity.

Increases in economic feedback are shown to lower emergy yield ratios (Figure 35). When investments were greater than 200E+12 sej/MWh electricity yield ratios approached unity. Wood fuels produced electricity with little or no net emergy yield compared with yields of 3-6 for electricity produced from nonrenewable sources.

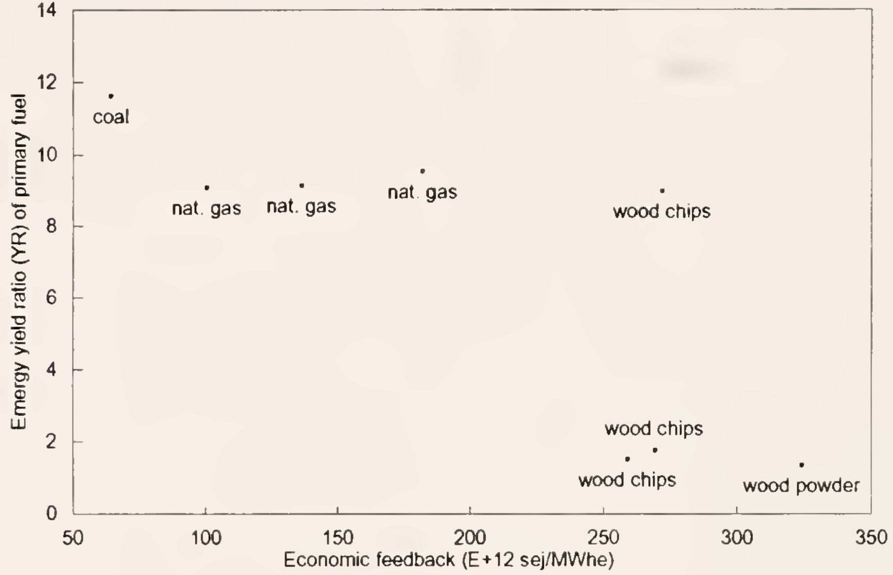
Optimal Investments for Primary Fuels and Electricity

Wood fuels required greater investments (i.e., higher emergy investment ratios) but generally had lower solar transformities than nonrenewable sources which are concentrated and require minimal processing (Figure 36a). Increases in economically derived inputs in fuel preparation are carried over with additional transformations of fuel to electricity. It may be that transformation efficiencies can be improved (i.e., lower solar transformities) with technological upgrading but because these efforts are emergy intensive, the emergy investment ratio increases rapidly with small reductions in efficiency. Coal appears to produce electricity at lower transformities and lower investment ratios than other fuel types studied (Figure 36b). Optimizing generation would lower emergy investments and produce electricity at the lowest possible transformity.

Thermodynamic Minimum Transformities for Primary Fuels and Electricity

Observed lower limits to electricity production at 100,000 sej/J suggest that efforts to increase efficiency past this point would produce minimal improvements but

(a) Primary fuel source



(b) Electricity generation

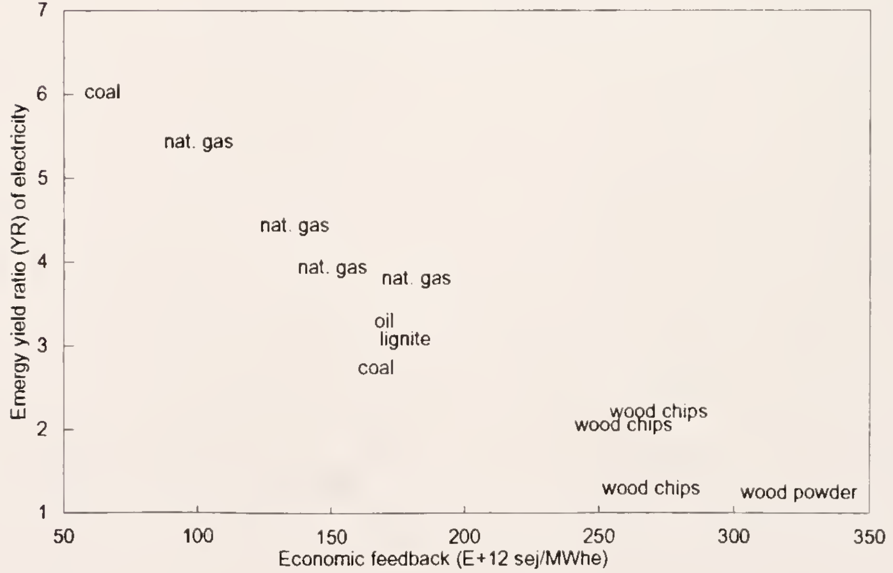
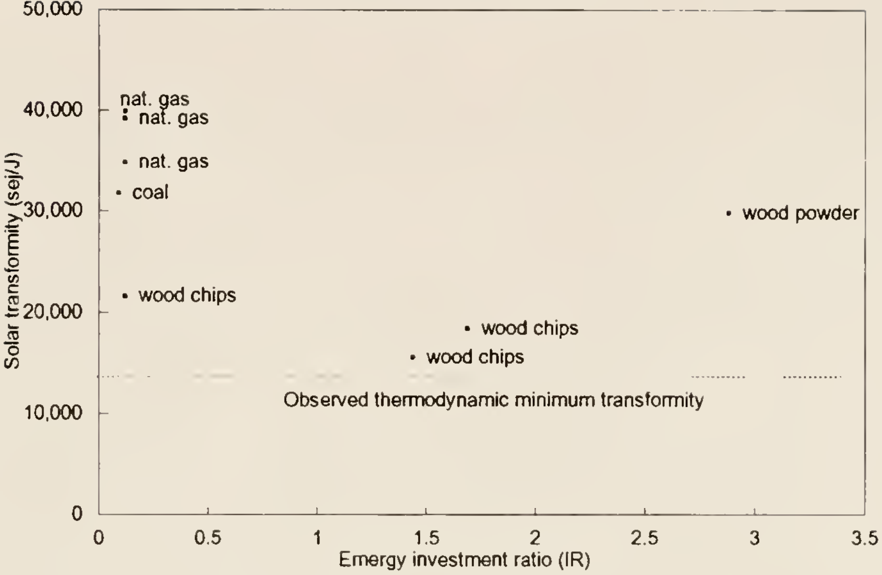
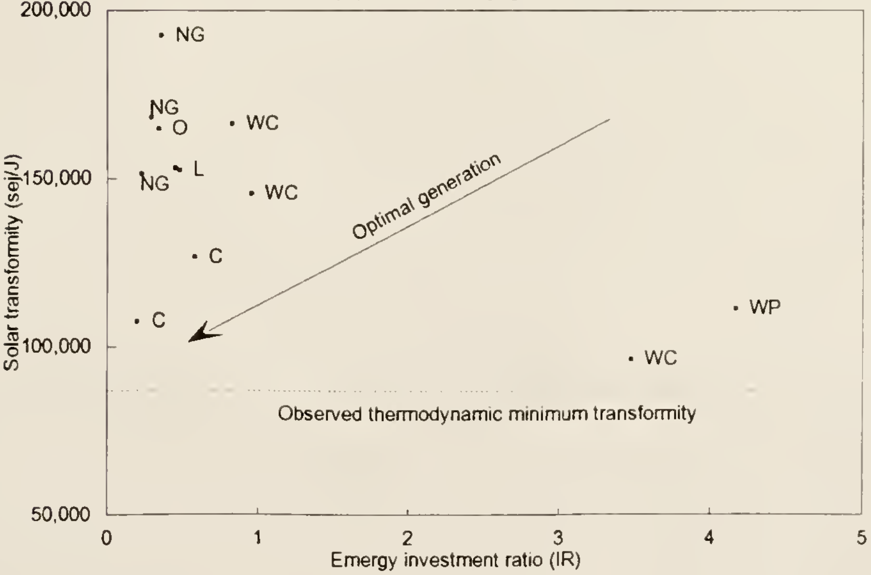


Figure 35. Emergy yield ratio as a function of economic feedback for evaluated systems of electricity generation: (primary fuel source; and (b) electricity.



(a) Primary fuel source



(b) Electricity generation

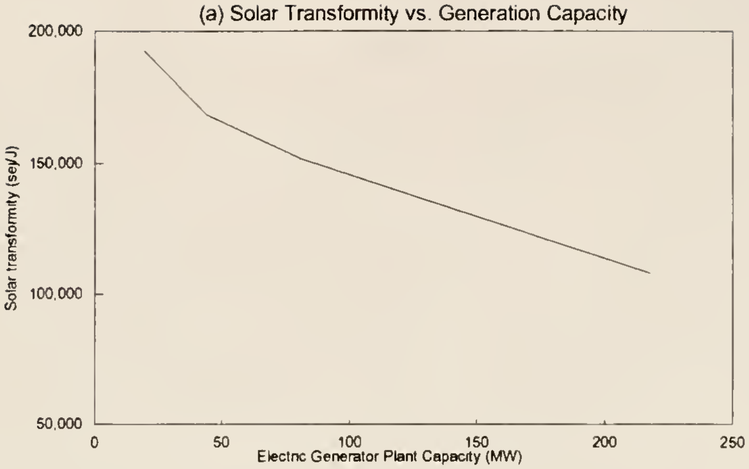
Figure 36. Solar transformity as a function of emergy investment ratio for evaluated systems of electricity generation.: (a) primary fuel source; and (b) electricity. C = coal; L = lignite; NG = natural gas; O = oil; WC = wood chips; and WP = wood powder.

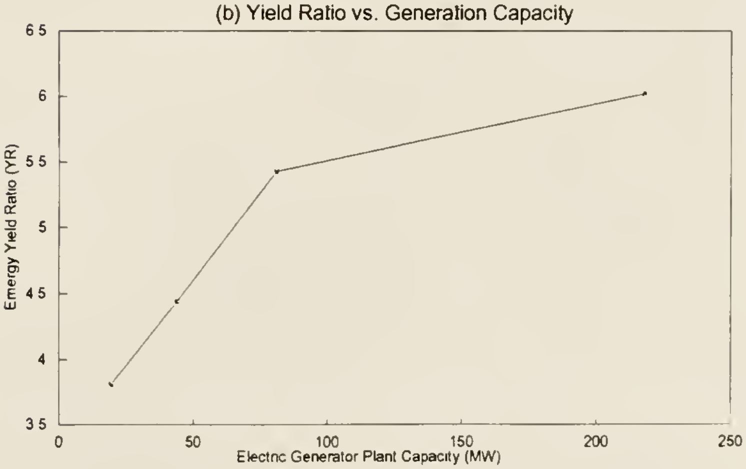
would require an increasingly larger share of additional resources drawn from economic sources which could possibly be used in other, more efficient sectors of the regional economy.

Evaluations of electric generator substations in Gainesville, Florida (Tables 18-21) suggest an economy of scales for plant capacity size, with increased efficiency (Figure 37a), higher yield ratios (Figure 37b) and lower investments (Figure 37c) as generator capacity increased. These examples indicate a diminishing returns with increasing plant size, suggesting an optimal output to maximize empower. Medium ranged generator stations perhaps operating near 100 MW capacity may be the most effective scale for transformation of fossil carbon fuels to electricity. Further increases in plant capacity may not lower the transformity below 1E+5 sej/J without substantive investments from economic sources, lowering yields and reducing competitiveness.

Comparison of Yield and Cycle Time from Forest Alternatives

Heat and electricity generation are compared in overview from three agroforest systems in Sweden with rotation periods ranging from 5 to 200 years. Values are based on earlier evaluations for each production system. Biomass production from old growth forests (Figure 9) are compared with wood delivered from managed forests (Figure 8) and from plantations (Figure 13). Transformations, investments and yields as functions of cycle time are given in Table 30. Emergy feedback per unit production of wood chips, heat and electricity were considered equal for all three systems.


(a) Solar Transformity vs. Generation Capacity


(b) Yield Ratio vs. Generation Capacity

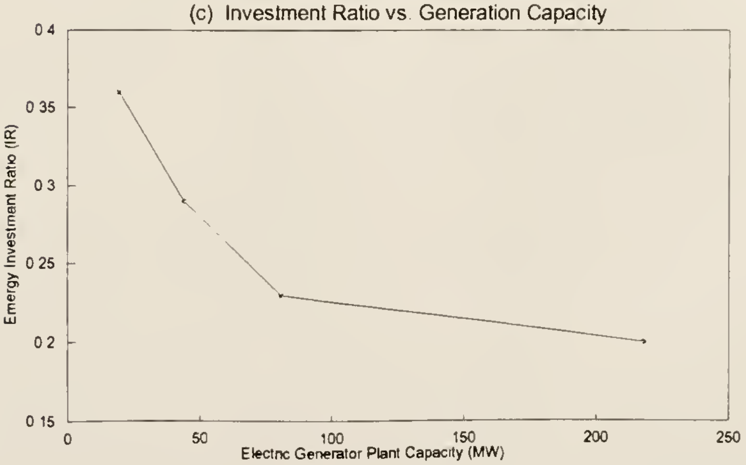

(c) Investment Ratio vs. Generation Capacity

Figure 37. Effect of increasing electric generating capacity on (a) solar transformity; (b) emergy yield ratio; and (c) emergy investment ratio from natural gas and coal-fired plants in Gainesville, Florida (data from Tables 18-21).

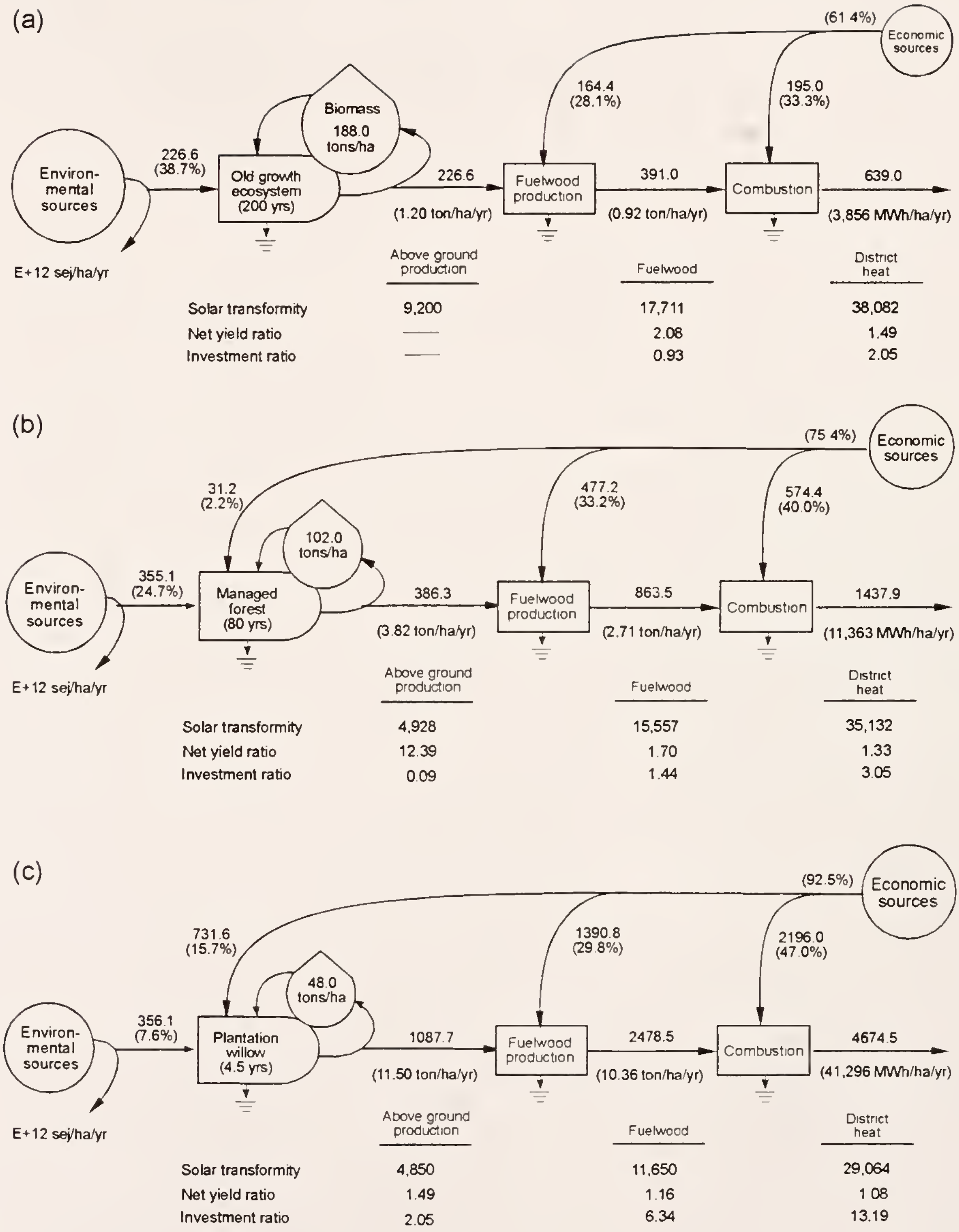
Table 30. Comparison of measurements for 3 agro-forest systems under different rotation schedules in Sweden: natural spruce ecosystem, 200 yrs (Figure 9b); managed spruce/pine forest, 80 yrs (Table 4); and plantation willow, 4.5 yrs (Table 13).

Process step	Annual yield (unit/ha/yr)	ST (sej/J)	YR (Y/F)	IR (F/I)	Emergy (Fi) per step (E+12 sej/ton)	Economic sources (F) (E+12 sej/ton)	Environmental sources (I) (E+12 sej/ton)	Equivalent area (ha/ha)	Additional costs (em$/unit)
1. Above ground production:	(tons/ha/yr)								(em$/ton)
Old growth spruce	1.20	9,200	---	---	0.00	0.00	188.78	9.6	0.00
Managed spruce/pine	3.82	4,928	12.39	0.09	8.17	8.17	92.96	3.0	5.45
Plantation willow	11.50	4,850	1.49	2.05	63.62	63.62	30.96	1.0	42.41
2. Harvested biomass:	(tons/ha/yr)								(em$/ton)
Old growth spruce	0.97	18,778	5.41	0.23	73.64	73.64	188.78	11.3	0.00
Managed spruce/pine	2.85	10,083	2.51	0.66	71.40	79.57	92.96	3.8	3.95
Plantation willow	10.90	6,720	1.33	3.02	31.60	95.21	30.96	1.0	14.38
3. Wood chips:	(tons/ha/yr)								(em$/ton)
Old growth spruce	0.92	17,711	2.08	0.93	101.00	174.64	188.78	11.3	0.00
Managed spruce/pine	2.71	15,557	1.70	1.44	101.00	180.57	92.96	3.8	3.95
Plantation willow	10.36	11,650	1.16	6.34	101.00	196.21	30.96	1.0	14.38
4. District heat:	(MWh/ha/yr)								(em$/GWh)
Old growth spruce	3,856	38,082	1.49	2.05	211.97	386.60	188.78	10.7	0.00
Managed spruce/pine	11,363	35,132	1.33	3.05	211.97	392.54	92.96	3.6	0.94
Plantation willow	41,296	29,064	1.08	13.19	211.97	408.18	30.96	1.0	3.61
5. Electricity:	(MWh/ha/yr)								(em$/GWh)
Old growth spruce	1,552	104,104	1.43	2.35	269.53	444.17	188.78	10.7	0.00
Managed spruce/pine	4,573	96,382	1.29	3.48	269.53	450.10	92.96	3.6	2.34
Plantation willow	16,626	81,694	1.07	15.04	269.53	465.74	30.96	1.0	8.96

Figure 38 summarizes annual inputs and yields. Results confirm analyses undertaken in this study. Plantation willow is about ten times as productive as old growth and about three times as productive as managed forests. Old growth ecosystems store 4 times the above ground biomass as short-rotation plantations and almost twice the quantity of managed forests. Contributions from environmental sources decline from almost 40% of the total for heat delivered from old growth (Figure 38a) to less than 10% for plantations (Figure 38c). Conversely, economic sources increase from 60% for heat delivered from mature forests to more than 90% for plantations.

Emergy Yield and Investment as Functions of Fuel Transformations

Solar transformities were lowest for products from short-rotation plantations (Figure 39a). Emergy yield ratios were greater (Figure 39b) and investment ratios were smaller (Figure 39c) for products from forest systems with longer cycle times. The differences in emergy yield between the 3 agroforest alternatives get smaller as biomass is transformed through production steps to heat and electricity. This is because the purchased emergy requirements increase with each step from silviculture to electricity generation, with each additional processing step requiring similar economic inputs per unit processed (Figure 40a). Heat and electricity generated from the fuelwood alternatives have yield ratios approaching unity, with little or no net emergy produced. Differences in emergy investment ratios between systems increased with transformations with heat and electricity produced from plantation fuelwood



(a)

	Above ground production	Fuelwood	District heat
Solar transformity	9,200	17,711	38,082
Net yield ratio	——	2.08	1.49
Investment ratio	——	0.93	2.05

(b)

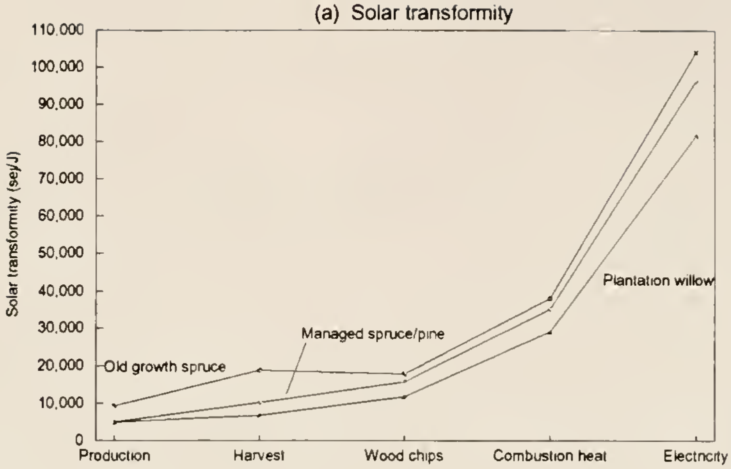
	Above ground production	Fuelwood	District heat
Solar transformity	4,928	15,557	35,132
Net yield ratio	12.39	1.70	1.33
Investment ratio	0.09	1.44	3.05

(c)

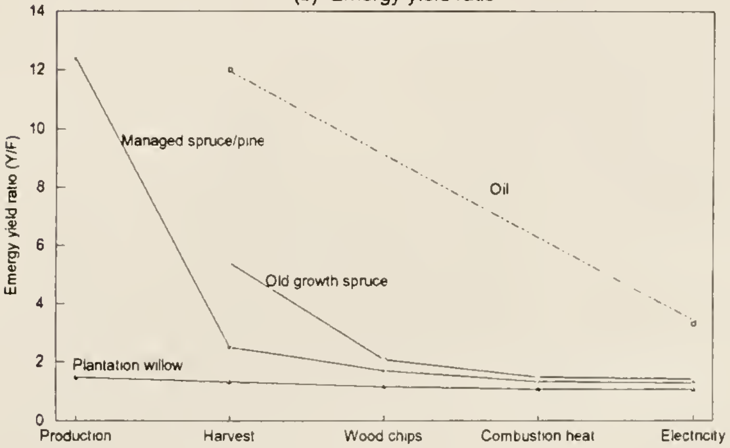
	Above ground production	Fuelwood	District heat
Solar transformity	4,850	11,650	29,064
Net yield ratio	1.49	1.16	1 08
Investment ratio	2.05	6.34	13.19

Figure 38. Systems diagrams of biomass production, storage, fuelwood development and heat generation from three agro-forest systems under different management schedules in southern Sweden: (a) natural, old growth spruce ecosystem; (b) silviculturally managed spruce/pine forest; and (c) short-rotation plantation willow. Refer to Table 30 for calculations.

(a) Solar transformity



(b) Emergy yield ratio



(c) Emergy investment ratio

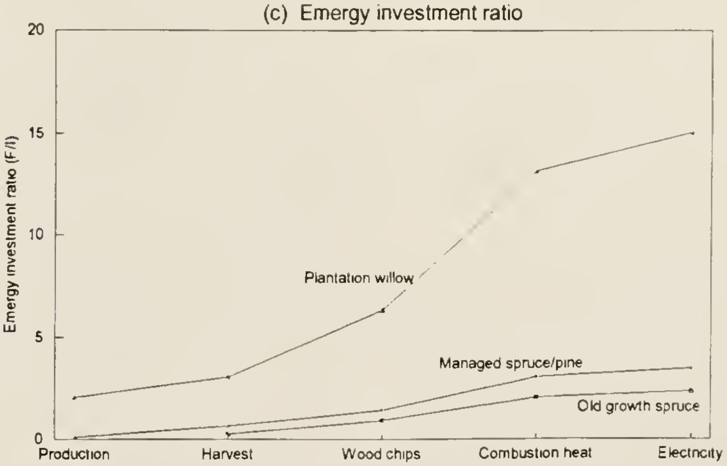
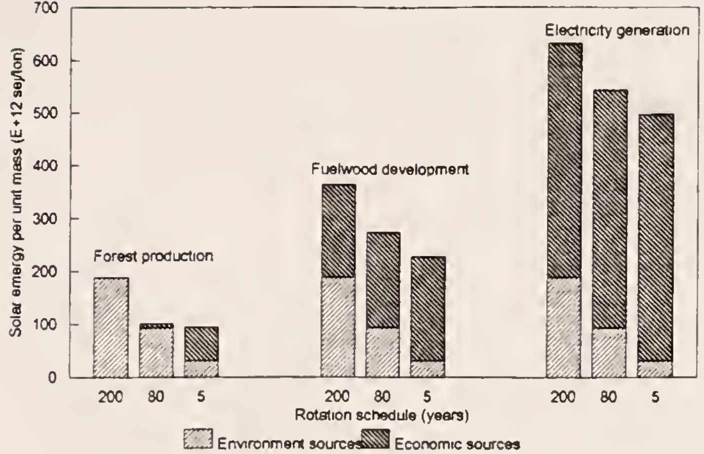
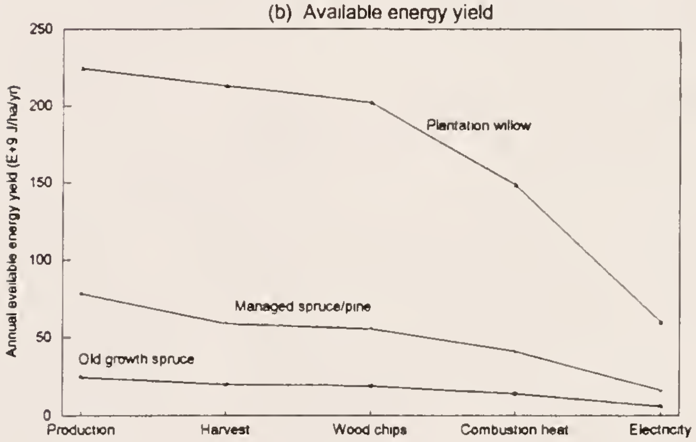


Figure 39. Comparisons of measurements for three agroforest systems under different rotation schedules for the development of fuelwood for possible heating and electricity generation: (a) solar transformity; (b) emergy yield ratio; and (c) emergy investment ratio.

(a) Solar emergy per unit fuelwood



(b) Available energy yield



(c) Equivalent land area requirements

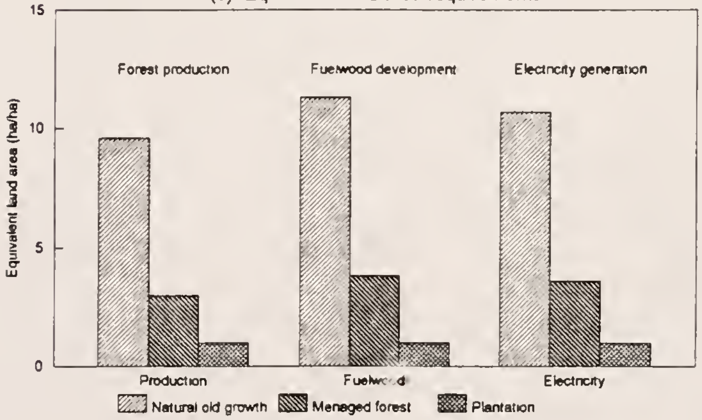


Figure 40. Comparisons of measurements for three agro-forest systems under different rotation schedules for the development of fuelwood for possible heating and electricity generation: (a) emergy per ton fuelwood; (b) annual available energy yield; (c) equivalent land area requirements.

requiring more than six times the feedback from economic sources than from natural forests (Figure 39c).

Oil and oil-fired electricity is also graphed in Figure 39b for comparison. A net emergy value of 12 for oil delivered is from Brown et al. (1993) for Alaskan north slope oil. An emergy yield ratio of 3.2 for oil-fired electricity, from Table 24 of this study, was more than twice as large as yield ratios for wood fired-electricity alternatives calculated here which range in this example from 1.43 for electricity from old growth wood to near unity (1.07) for electricty from plantation willow. Oil, with higher net yields than wood fuels, is currently a more competitive fuel than biomass fuels which require additional processing to concentrate the lower quality energy for high temperature combustion. These additional data points support the observation made here that large net yields are rapidly diminished as the fuel source is transformed into higher quality uses of heat and electricity. Primary fuels must therefore have large yield ratios if these fuels are to contribute as sources and net contributors of energy.

Energy Yield and Energy Quality as Functions of Cycle Time and Processing

Although there is more heat per ton fuelwood from mature forests, the improved energy efficiency is dampened by the greater output from younger intensively managed systems. Measuring available energy, annual yields are greater for plantation systems, but because plantation fuelwood is of lower quality, by the time production is transformed into heat and electricity, the differences in available energy yield are reduced between systems (Figure 40b).

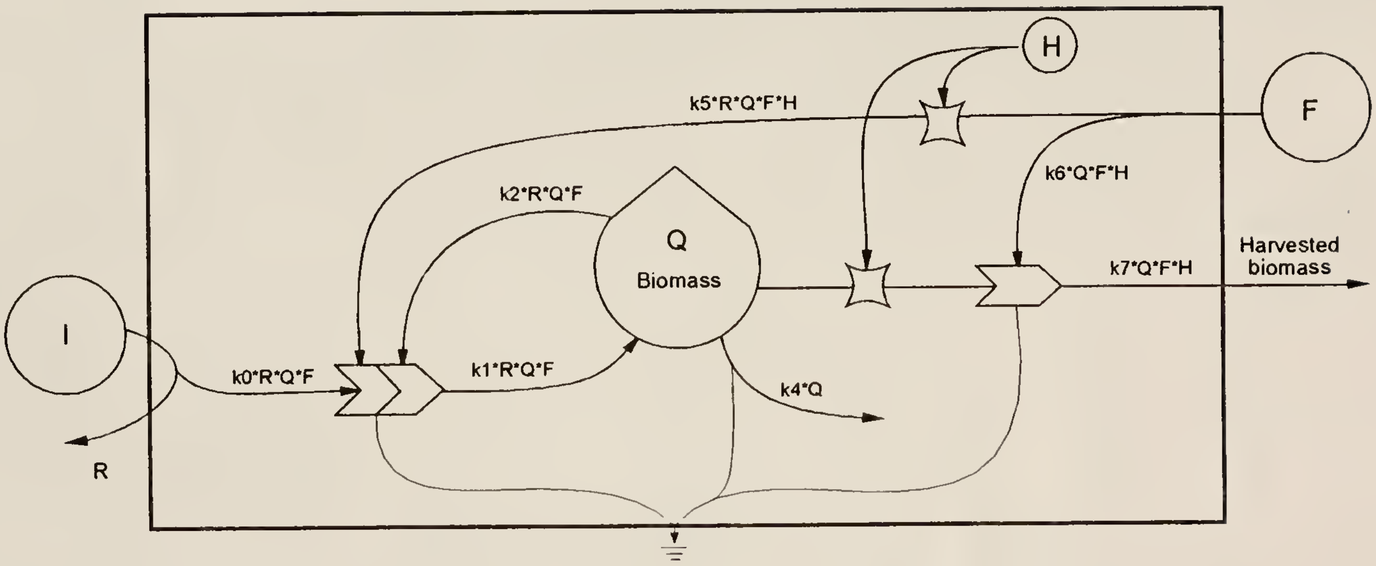
Relationship of Area and Time in Biomass Production

It would take almost 10 hectares of old growth and 3 hectares of managed forest to yield an equivalent amount of production from plantations (Figure 40c). This land area ratio increases slightly once production has been harvested and chipped for fuelwood because a smaller percentage of production is available for harvest in natural and older systems. Equivalent land areas are reduced slightly once electricity is generated since fuelwood from older forests has a higher heat content.

Computer Models of Systems Principles

Simulation of Emergy Yield and Cycle Time

Figure 41 is a computer model developed to verify the observation made here that emergy yield ratio increases as a function of cycle time. The model was calibrated using forest production data from managed spruce/pine forests of Sweden (Table 4). The model is calibrated in Table 31 and a computer simulation program is given in Appendix A. Biomass production (Y_1) is shown as a function of biomass (Q), available environmental sources (R) and economic inputs (F_1). Harvested biomass (Y_2) is a function of Q and economic inputs (F_2). Gross production ($GP = k_1*R*Q*F$) increased with cycle time, with net production ($NP = GP - k_2*R*Q*F - k_4*Q$) maximized at 12 tons/ha/yr in 62 years, approaching zero at its natural rotation of 120 years (Figure 42a). Above ground biomass (Q) increased with cycle time and levels off at about 160 tons/ha (Figure 42b).



Energy equations:

$R = J / (1 + k0*Q*F)$ = Remainder of environmental inflows

$I = k0*R*Q*F$ = Environmental power inflow

$F1 = k5*R*Q*F*H$ = Silviculture feedback

$F2 = k6*Q*F*H$ = Harvest feedback

$GP = k1*R*Q*F$ = Gross production

$Y1 = (k1*R*Q*F) - (k4*Q + k2*R*Q*F)$ = Net production

$Y2 = k7*Q*F*H$ = Harvested biomass

EMERGY equations:

$EmI = StI * (k0*R*Q*F)$ = Emergy of environmental inflows

$EmF1 = StF * F1$ = Emergy of silviculture feedback

$EmF2 = StF * F2$ = Emergy of harvest feedback

$EmGP = EmI + EmF1$ = Emergy of gross production

$StGP = EmGP / (k1*R*Q*F)$ = Transformity of gross production

$StY1 = (EmI + EmF1) / Y1$ = Transformity of net production

$StY2 = (EmI + EmF1 + EmF2) / Y2$ = Transformity of harvested biomass

$StQ = EmQ / Q$ = Transformity of biomass storage

Figure 41. Systems diagram and equations for simulation model determining biomass production and emergy yield ratio as a function of time for agro-forest systems. Pathway values, initial conditions and calibration of coefficients are given in Table 31. Computer program is listed in Appendix A.

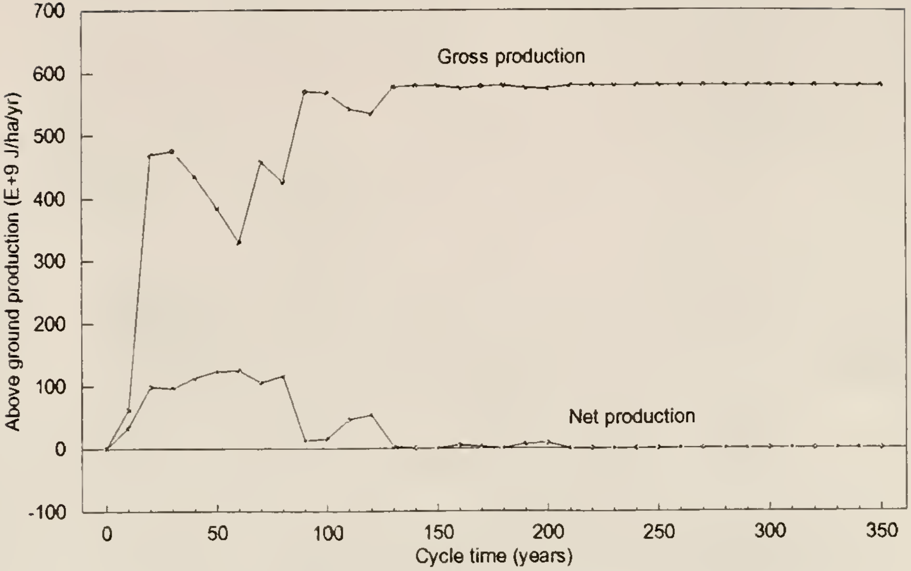
Table 31. Pathway variables, initial conditions and calibration of transfer coefficients for computer simulation model of biomass production and emergy yield ratio as a function of cycle time (YR-CT.BAS).[a] Model is diagrammed in Figure 41. Model is calibrated for managed spruce/pine forest in southern Sweden (Table 4).

Note	Pathway		Equation		Value (E+9 J/ha/yr)	Coefficient calibration
Sources:						
1.	Environmental inflow	J	= 40.00 E+9 J/ha/yr			
2.	Economic inflow	F	= 0.66 E+9 J/ha/yr			
Storage:						
3.	Above ground biomass	Q	= 2500.00 E+9 J/ha			
Pathway values (E+9 J/ha/yr):						
4.	Environmental use	I	= ko*R*Q*F	=	20.00	k0 = 6.06E-4
5.	Eniron. remainder	R	= J/(1 + k0*Q*F)	=	20.00	
6.	Gross production	GP	= k1*R*Q*F	=	500.00	k1 = 0.15152
7.	Forest feedback		= k2*R*Q*F	=	0.50	k2 = 1.52E-5
8.	Forest metabolism		= k4*Q	=	419.50	k4 = 0.1678
9.	Net production	Y_1	= GP - (k2*R*Q*F +k4*Q)	=	80.00	
10.	Silviculture feedback	F_1	= k5*R*Q*F*H	=	0.06	k5 = 1.82E-6
11.	Harvest feedback	F_2	= k6*Q*F*H	=	0.60	k6 = 3.64E-4
12.	Harvested biomass	Y_2	= k7*Q*F*H	=	60.00	k7 = 0.3636

Notes.

1. Chemical potential energy in rain = (0.8 m/yr) (1E+4 m^2/ha) (1000 kg/m^3) (4.94E+3 J/kg) = 4.0E+10 J/ha/yr
2. Economic sources = F1 + F2 = items 10 + 11 = 6.6E+8 J/ha/yr
3. Above ground biomass storage (Q) = (120 tons/ha) (2.052E+10 J/ton) = 2.5E+12 J/ha
4. Environmental sources used = evapo-transpired rain = (50%) (4.0E+10 J/ha/yr; note 1) = 2.0E+10 J/ha/yr
5. Environmental sources remaining at start = items 1 - 2 = 2.0E+10 J/ha/yr
6. Gross production: est. 15% of net production (item 8) = 5.0E+11 J/ha/yr
7. Forest feedback: est. 1% of gross production (item 6) = 5.0E+8 J/ha/yr
8. Forest metabolism: GP - NP - feedback = 4.2E+11 J/ha/yr
9. Net above ground production (Y_1) = (9.0 m^3/ha/yr) (0.425E+6 g/m^3) (2.052E+4 J/g) = 8.0E+10 J/ha/yr
10. Silviculture feedback: fuel use = (1.57 liters/ha/yr) (35.6E+6 J/l) = 6.0E+7 J/ha/yr
11. Harvest feedback: fuel use = (2.5 liters/m^3) (6.7 m^3/ha/yr) (35.6E+6 J/l) = 6.0E+08 J/ha/yr
12. Harvested biomass (Y_2) = (6.7 m^3/ha/yr) (4.25E+4 g/m^3) (2.05E+4 J/g) = 6.0E+10 J/ha/yr

(a) Forest production as a function of cycle time



(b) Above ground biomass as a function of cycle time

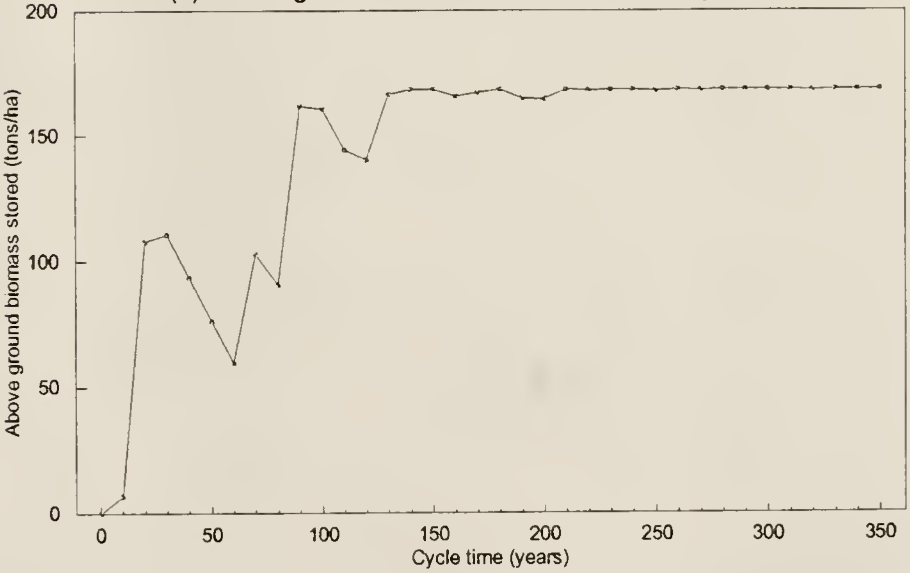


Figure 42. Computer simulation of forest development as a function of cycle time: (a) gross and net production; and (b) above ground biomass accumulation. Model is given in Figure 41.

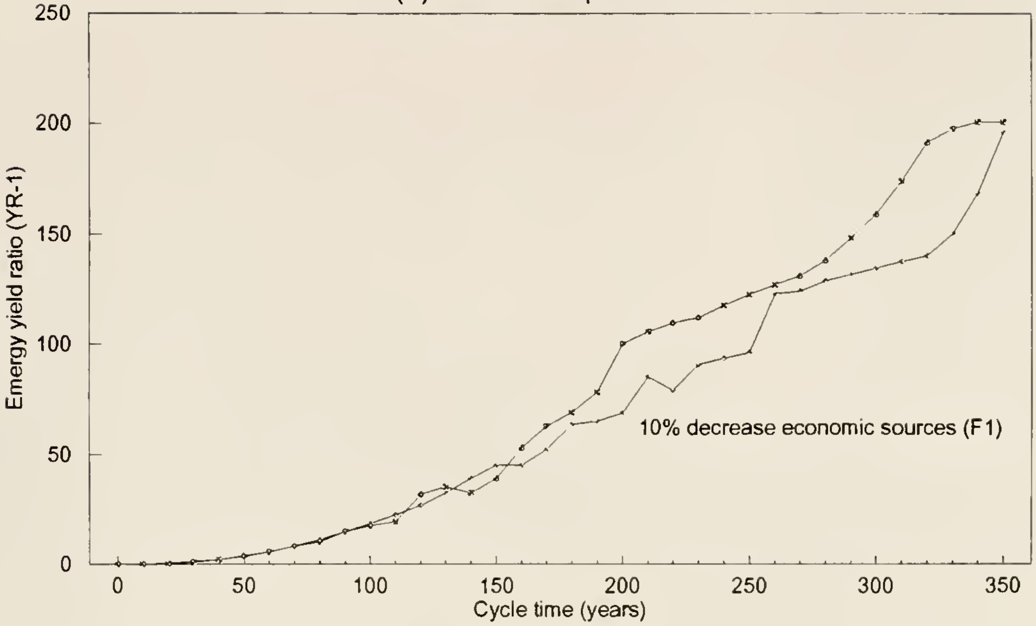
Emergy yield ratios for both production (YR_1) and harvested biomass (YR_2) is shown to increase with increasing cycle time (Figure 43). Even though very large yield ratios for production (Figure 43a) are obtained with rotations longer than the natural forest cycle, the emergy yield ratio once the biomass is harvested was only about one-tenth the value. Lowering economic inputs to production (Figure 43a) appeared to lower the emergy yield ratio with rotations greater than 120 years. Increasing economic inputs to harvest the biomass (Figure 43b) produced a declining emergy return on investments.

These simulations support the postulate that emergy yield for systems using flow-limited natural resources is a function of growth period. Emergy yield is not a positive linear function of growth period; diminishing increases in emergy yield ratios are obtained with rotation periods above the period of accelerated forest growth. Greater incremental increases in emergy yield ratios are achieved with shorter rotations. These relationships emphasize the limits of biomass production systems to deliver competitive yields when non-renewable primary energy sources delivering higher net yields are available.

Mathematical Relationship of Emergy Yield and Investment Ratios

An inverse relationship of yield and investment ratios was identified for agroforest system production and harvest (Figure 44). As resources are upgraded through value-added economic transformations, investments (F_i) become large, environmental source inputs (I) become negligible and the emergy yield ratio approaches unity. Investment ratios ($IR_i = F_i/I$) and yield ratios ($YR_i = Y_i/F_i$) are

(a) Net forest production



(b) Harvested biomass

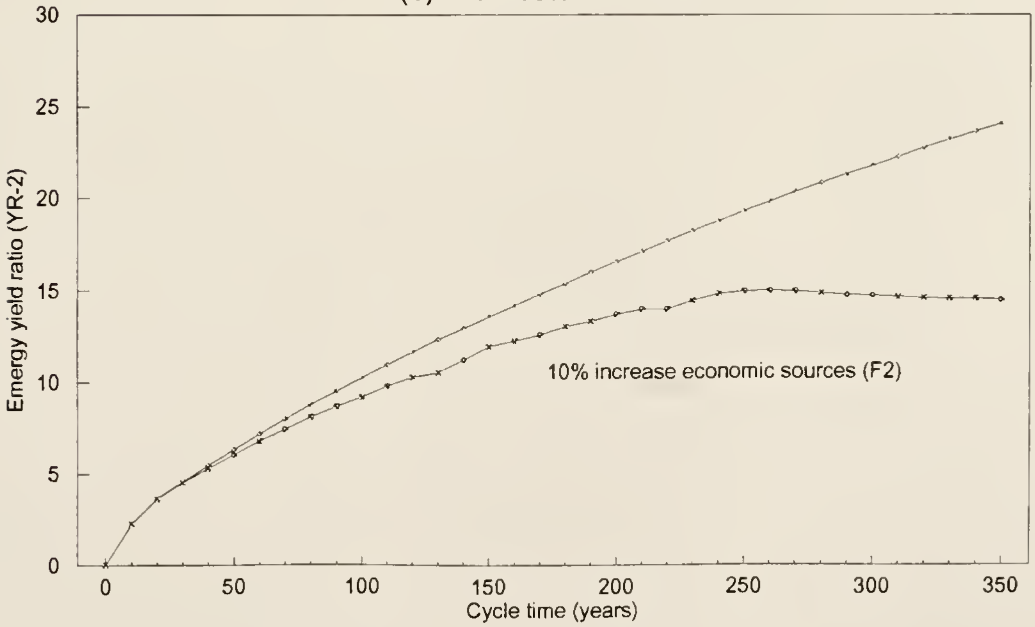
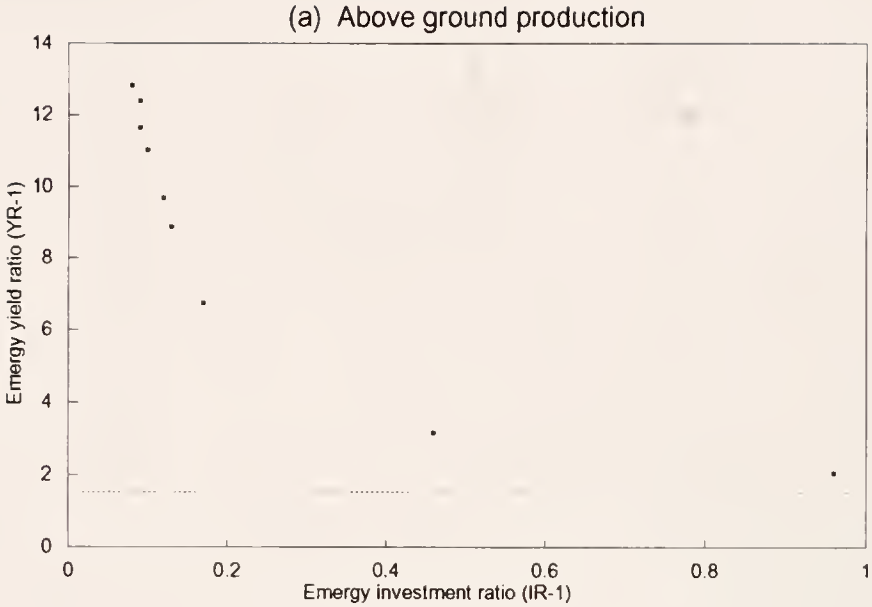
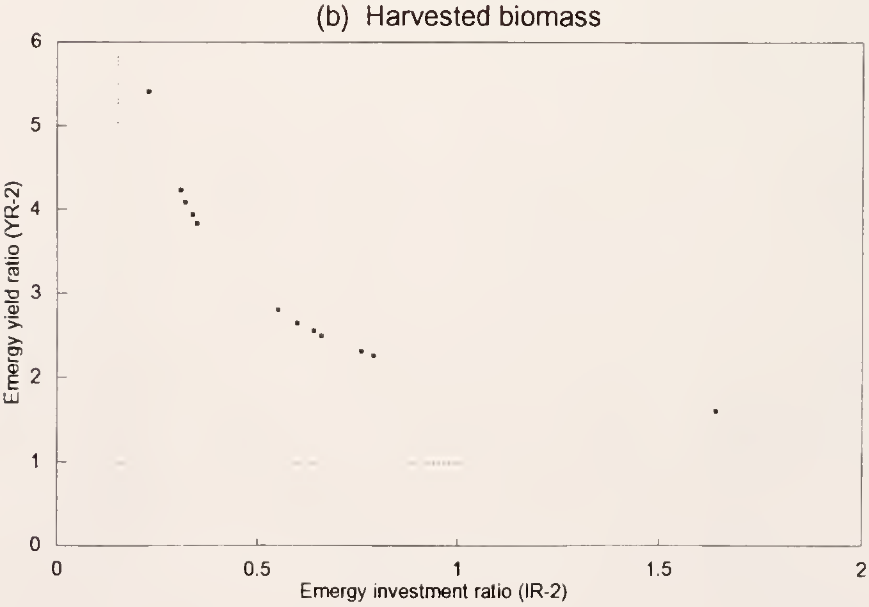


Figure 43. Computer simulation of emergy yield ratio as a function of cycle time: (a) net above ground production (YR_1); and (b) harvested biomass (YR_2). Model is given in Figure 41.



(a) Above ground production



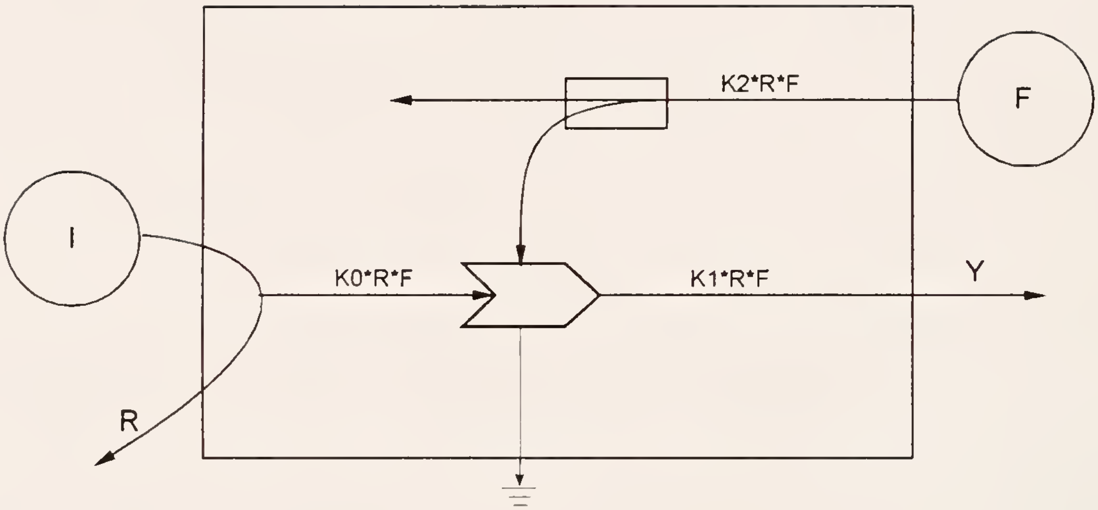
(b) Harvested biomass

Figure 44. Emergy yield ratio as a function of emergy investment ratio for evaluated agro-forest ecosystems: (a) above ground production; and (b) harvested biomass.

related as hyperbolic functions of one another as a consequence of the mathematical derivation of system yield (Y_1) as the sum total of ecologic inputs (I) and economic inputs (F_1) (refer to Figure 4b and Table 1 for definitions).

This relationship is diagrammed and mathematically defined in Figure 45 for a general production system receiving environmental and economic inputs. A computer program is listed in Appendix B. This inverse relationship, set by theory, agrees with data from analyses undertaken in this work and is confirmed by this computer minimodel. Emergy yield ratio drops rapidly as economic investments become more than a third of the total inputs supporting production (i.e., IR = 0.5) (Figure 46a). Similarly, investments made to increase production may increase transformities of products (Figure 46b), reducing system efficiency and generating products that can be made for less in other, better organized sectors.

This intuitive function relating yield and investment can be used to identify competitive options for energy proposals. Typical sectors of a region can be compared with alternatives for both emergy investments and yields (refer to Figure 5). By matching investments with environmental sources at or below that typical of a region, a production sector would likely be economical in competition with other sectors. In the case of primary fuels used to drive economic processes, the requisite high yield ratios would dictate that investments remain small relative to environmental sources. If processing costs raise investment ratios above 0.5 there remains little net emergy available to generate high quality heat, electricity, and information or to drive other economic processes.



Equations:

R = J / (k0*R*F) = Remainder of environmental inflow

I = k0*R*F = Environmental power inflow

F = k2*R*F = Economic investment

Y = k1*R*F = Product energy

EmI = StI * I = Emergy of environmental inflows

EmF = StF * F = Emergy of economic investments

EmY = EmI +EmF = Emergy of product

StY = EmY / Y = Solar transformity of product

YR = EmY / EmF = Emergy yield ratio of product

IR = EmF / EmI = Emergy investment ratio of product

Figure 45. Systems diagram and equations for minimodel of general production relating indices of emergy yield (YR) and investment (IR). Calibrated computer program is listed in Appendix B.

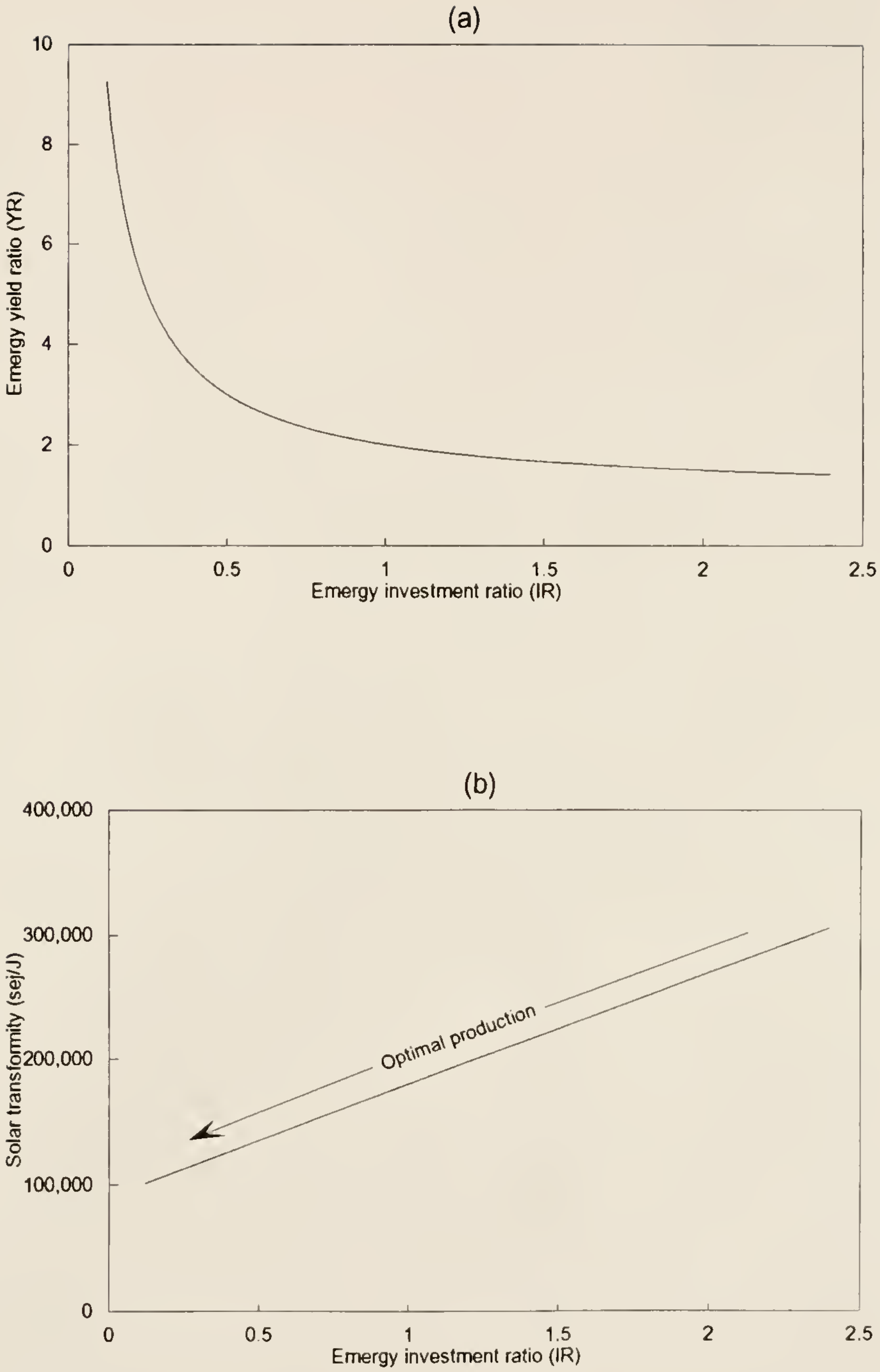


Figure 46. Computer derivation of the relationships between (a) emergy yield and investment ratios and (b) solar transformity and emergy investment for minimodel of general production. Model is shown in Figure 45.

Regional Values

Forest Production

Relating emergy to regional economies, emdollar values are given in Table 32 for biomass production and storage for evaluated agroforest systems. Although emdollar values for production are higher for plantations and managed forests, a greater proportion is derived from economic feedback than in natural forests where the contribution is delivered free from environmental sources. The emdollar value of stored biomass in natural systems is generally higher than in short-rotation systems because they store more biomass during forest cycles.

Transformities for forest production and above ground biomass are shown to increase with increasing empower (Figure 47). These relationships indicate that transformities could be used to measure biomass accrual and storage rates, and that empower (i.e., annual per hectare emergy-use) could be used as a correlate of regional value for production systems.

Emergy-based measures of regional value for forest production and biomass storage (Table 32) compared with current market costs of carbon emissions abatement (McPherson et al. 1994) reveal two overview prospects: 1) removal of greenhouse gases such as carbon dioxide may be of greater value to regional and global economies than currently valued by monetary markets; and 2) multiple-use of forests as carbon sinks and other ecosystem services may represent a greater contribution to regional economies than delivered from extractions based on market prices.

Table 32. Emdollar values for forest production and biomass storage in agroforest ecosystems evaluated in this study.

Note	Forest type	Rotation age (years)	Annual biomass production[a]		Stored above ground biomass[b] (em$/ha)
			Environmental contribution (em$/ha/yr)	Economic contribution (em$/ha/yr)	
Short-rotation systems:					
1.	Willow plantation	4.2	234	477	2,976
2.	Fuelwood plantation	5	291	476	3,832
3.	Eucalyptus plantation	5.8	297	283	3,452
4.	Siris plantation	11	605	281	7,027
Managed forests:					
5.	Southern slash pine	25	468	60	8,648
6.	Temperate loblolly pine	30	154	27	5,402
7.	Temperate mixed hardwoods	60	153	15	10,118
8.	Boreal spruce/pine	80	232	20	6,742
Natural ecosystems:					
9.	Tropical palm forest	27	455	0	4,756
10.	Tropical dry forest	47	396	0	2,584
11.	Tropical lowland tabonuco	59	963	0	18,185
12.	Tropical premontane colorado	62	455	0	8,130
13.	Mixed northern coniferous	100	308	0	11,597
14.	Tropical cloud forest	172	88	0	1,965
15.	Spruce ecosystem	200	148	0	18,124
16.	Tropical lowland rainforest	300	768	0	14,478

Notes.

a. Em$ value for above ground net primary productivity = (solar emergy/ha/yr) / (solar emergy-use/$ for country location):

1. Willow plantation: (1086.7E+12 sej/ha/yr) / (1.53E+12 sej/$, Sweden; Doherty et al. 1993) = 710.26 em$/ha/yr; F = (710.26 em$/ha/yr) / (1.49) = 476.69 em$/ha/yr; I = (710.26 - 476.69) em$/ha/yr = 233.58 em$/ha/yr

2. Melaleuca/eucalyptus plantation: (2454.2E+12 sej/ha/yr) / (3.2E+12 sej/$, U.S. 1980; Odum 1995) = 766.94 em$/ha/yr; F = (766.94 em$/ha/yr) / (1.61) = 476.36 em$/ha/yr; I = (766.94 - 476.36) em$/ha/yr = 290.58 em$/ha/yr

3. Eucalyptus plantation: (10.2 ton/ha/yr) (1.62E+10 J/ton) (12,952 sej/J; Table 26) / (3.69E+12 sej/$) = 580.00 em$/ha/yr; F= (580.00 em$/ha/yr) / (2.05) = 282.93 em$/ha/yr; I = (580.00 - 282.93) em$/ha/yr = 297.07 em$/ha/yr

Table 32--continued.

4. Siris plantation: (10.4 ton/ha/yr) (1.674E+10 J/ton) (8,344 sej/J; Table 10) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 885.77 em$/ha/yr; F= (885.77 em$/ha/yr) / (3.15) = 281.2 em$/ha/yr; I = (885.77 - 281.2) em$/ha/yr = 604.57 em$/ha/yr

5. Slash pine: (9.6 ton/ha/yr) (1.88E+10 J/ton) (5829 sej/J; Table 6) = 1.06E+15 sej/ha/yr / (2.0E+12 sej/$, U.S.; Odum 1994) = 527.13 em$/ha/yr; F = (527.13 em$/ha/yr) / (8.86) = 59 50 em$/ha/yr; I = (527.13 - 59.50) em$/ha/yr = 467.63 em$/ha/yr

6. Temperate loblolly pine: (721.0E+12 sej/ha/yr) / (4.0E+12 sej/$, U.S. 1978; Odum 1995) = 180.25 em$/ha/yr; F = (180.25 em$/ha/yr) / (6.74) = 26.74 em$/ha/yr; I = (180.25 - 26.74) em$/ha/yr = 153.51 em$/ha/yr

7. Temperate mixed hardwoods: (675.0E+12 sej/ha/yr) / (4.0E+12 sej/$, U.S. 1978; Odum 1995) = 168.75 em$/ha/yr; F = (168.75 em$/ha/yr) / (11.03) = 15.30 em$/ha/yr; I = (168.75 - 15.30) em$/ha/yr = 153.45 em$/ha/yr

8. Boreal spruce/pine forest: (3.8 ton/ha/yr) (2.05E+10 J/ton) (4928 sej/J; Table 4) = 3.86E+14 sej/ha/yr / (1.53E+12 sej/ha/yr, Sweden; Doherty et al. 1993) = 252.23 em$/ha/yr; F = (252 em$/ha/yr) / (12.39) = 20.36 em$/ha/yr; I = (252.23 - 20.36) em$/ha/yr = 231.87 em$/ha/yr

9. Palm forest: (7.46E+14 sej/ha/yr; Table 11) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 455 em$/ha/yr = I

10. Guánica dry forest: (6.49E+14 sej/ha/yr; Table 11) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 396 em$/ha/yr = I

11. Tabonuco forest: (1.58E+15 sej/ha/yr; Table 11) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 963 em$/ha/yr =I

12. Colorado forest: (7.46E+14 sej/ha/yr; Table 11) / (1.64E+12 sej/$, Puerto Rico, Doherty et al. 1994) = 454.9 em$/ha/yr =I

13. Northern mixed coniferous: (3.19 ton/ha/yr) (2.052E+10 J/ton) (7188 sej/J; Figure 9) = 4.71E+14 sej/ha/yr / (1.53E+12 sej/ha/yr, Sweden; Doherty et al. 1993) = 307.53 em$/ha/yr = I

14. Cloud forest: (1.44E+14 sej/ha/yr; Table 11) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 87.8 em$/ha/yr = I

15. Old growth spruce: (1.20 ton/ha/yr) (2.052E+10 J/ton) (9200 sej/J; Figure 9) = 2.27E+14 sej/ha/yr / (1.53E+12 sej/ha/yr, Sweden; Doherty et al. 1993) = 148.07 em$/ha/yr = I

16. Tropical rainforest: (18.57 ton/ha/yr) (2.0E+10 J/ton) (14264 sej/J) = 5.30E+15 sej/ha/yr / (6.9E+12 sej/$, Brazil; Comar 1993) = 767.78 em$/ha/yr; F = (767.78 em$/ha/yr) / (8.97) = 85.59 em$/ha/yr; I = (767.78 - 85.59) em$/ha/yr = 682.19 em$/ha/yr

b. Em$ value for above ground biomass = (solar emergy/ha) / (sej/$ for country location):

1. Willow plantation: (48.0 tons/ha) (1.95E+10 J/ton) (4850 sej/J) / (1.53E+12 sej/$, Sweden; Doherty et al. 1993) = 2967 em$/ha

Table 32--continued.

2. Melaleuca/eucalyptus plantation: (65 tons/ha) (1.674E+10 J/ton) (11,270 sej/J) / (3.2E+12 sej/$, U.S. 1980; Odum 1995) = 3832 em$/ha

3. Eucalyptus plantation: (60.7 tons/ha) (1.62E+10 J/ton) (12,952 sej/J) / (3.69E+12 sej/$, Thailand; Brown and McClanahan 1992) = 3452 em$/ha

4. Siris plantation: (82.5 ton/ha) (1.674E+10 J/ton) (8,344 sej/J; Table 10) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 7027 em$/ha

5. Slash pine: (14983 g/m^2, tree wood biomass + 659 g/m^2, tree foliage biomass + 14 g/m^2, understory wood biomass + 127 g/m^2, understory foliage biomass) = 15783 g/m^2 (1.88E+4 J/g) (1E+4 m^2/ha) (5829 sej/J) = 1.73E+16 sej/ha / (2.0E+12 sej/$, U.S., 1990; Odum 1995) = 8648 em$/ha

6. Temperate loblolly pine: (265 ton/ha) (2.0E+10 J/ton) (4075 sej/J) / (4.0E+12 sej/$, U.S. 1978; Odum 1995) = 5402 em$/ha

7. Temperate mixed hardwoods: (226 ton/ha) (1.82E+10 J/ton) (9834 sej/J) / (4.0E+12 sej/$, U.S. 1978; Odum 1995) = 10,118 em$/ha

8. Boreal spruce/pine forest: (102 ton/ha) (2.05E+10 J/ton) (4928 sej/J; Table 4) = 1.03E+16 sej/ha / (1.53E+12 sej/$, Sweden; Doherty et al. 1993) = 6735 em$/ha

9. Palm forest: (199.1 ton/ha) (1.63E+10 J/ton) (2343 sej/J) = 7.80E+15 sej/ha / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 4756 em$/ha

10. Guánica dry forest: (45.0 ton/ha) (1.67E+10 J/ton) (5624 sej/J) = (4.24E+15 sej/ha) / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 2584 em$/ha

11. Tabonuco forest: (197.9 ton/ha) (1.67E+10 J/ton) (9000 sej/J) = 2.98E+16 sej/ha / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 18185 em$/ha

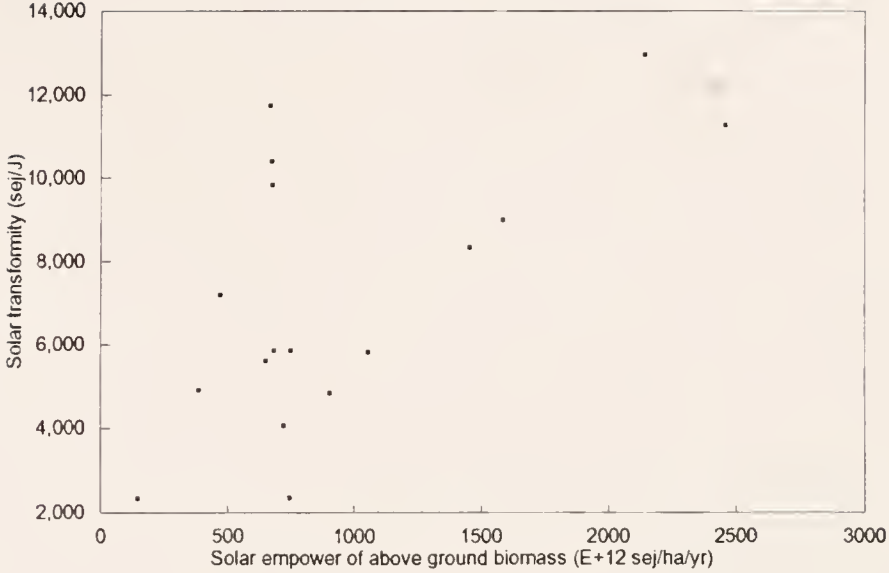
12. Colorado forest: (135.8 ton/ha) (1.67E+10 J/ton) (5864 sej/J) = 1.33E+16 sej/ha / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 8130 em$/ha

13. Northern mixed coniferous (100 yrs): (120.3 ton/ha) (2.05E+10 J/ton) (7188 sej/J; Figure 9) / (1.53E+12 sej/$, Sweden; Doherty et al. 1993) = 11,597 em$/ha

14. Cloud forest: (82.9 ton/ha) (1.67E+10 J/ton) (2322 sej/J) = 3.22E+15 sej/ha / (1.64E+12 sej/$, Puerto Rico; Doherty et al. 1994) = 1965 em$/ha

15. Old growth spruce ecosystem: (188 ton/ha) (2.052E+10 J/ton) (7188 sej/J; Figure 9) = 2.77E+16 sej/ha / (1.53E+12 sej/$, Sweden; Doherty et al. 1993) = 18,124 em$/ha

16. Tropical rainforest: (350 tons/ha) (2.0E+10 J/ton) (14,264 sej/J) / (6.9E+12 sej/$, Brazil; Comar 1993) = 14,478 em$/ha


(a) Above ground production (tons/ha/yr)

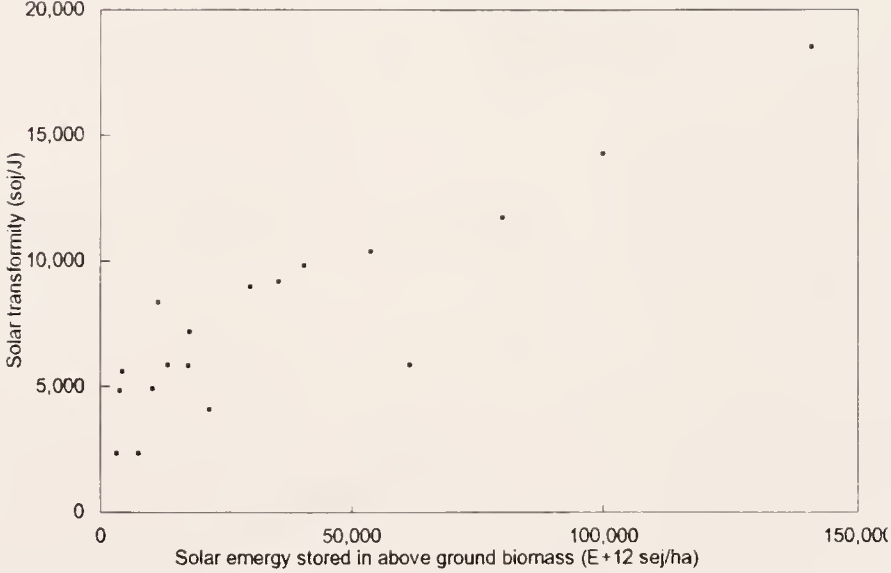

(b) Above ground biomass (tons/ha)

Figure 47. Solar transformity as a function of biomass production and storage for evaluated agro-forest ecosystems: (a) empower of above ground production; and (b) emergy stored in above ground biomass.

Regional Water Supply

Similarly, surface water supplied from elevated forest watersheds is shown to provide macro-economic value to downstream users (Table 33). Emdollar values for natural forests in Puerto Rico ranged from 2,600 em$/ha/yr for lowland forests to 3,800 em$/ha/yr for montane systems. Gravitational potential emergy decreased at lower elevations (Figure 48a) but chemical potential emergy increased at lower elevations (Figure 48b) as gravitation potential is used up concentrating chemical potential as water moves down stream. Contributions of upstream and high elevation ecosystems to regional empower and incentives for watershed protection are identified using emergy evaluations.

Current market assessments in Puerto Rico for secondary lowland rainforest land (average 2,800 $/ha; Caribbean National Forest unpublished data) suggest that: 1) emdollar value of carbon stored in above ground biomass is as much as 8 times the market value; and 2) that economic investments could be returned in less than two years from annual ecosystem services of water supply and forest production. Environmental transformations of renewable energy sources supply regional economies with services and co-products maximizing regional wealth by freeing up economically derived sources for use in other sectors.

Table 33. Emdollar values for surface water runoff from four forested watersheds in the Luquillo Experimental Forest, Puerto Rico.[a]

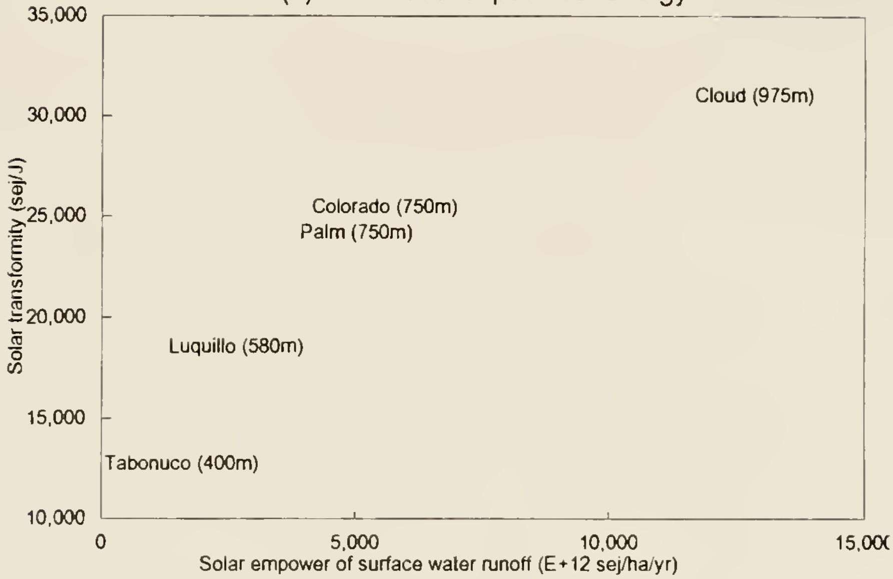
Note	Surface water source	Per hectare flux (em$/ha/yr)	Forest total (E+6 em$/yr)
1.	Cloud forest	3,763	1.55
2.	Colorado forest	3,573	11.74
3.	Palm forest	3,235	6.19
4.	Tabonuco forest	2,621	14.83
5.	Luquillo total:		34.31

Notes.

Emdollar (em$) values of surface water estimated as chemical potential emergy (Table 14) (value assumed to include the co-product of physical potential emergy) divided by the emergy/money ratio for Puerto Rico (Doherty et al. 1994).

1. Cloud forest: (6.19E+15 sej/ha/yr) / (1.64E+12 sej/$) = 3763 em$ha/yr (412 ha) = 1.55E+6 em$/yr
2. Colorado: (5.87E+15 sej/ha/yr) / (1.64E+12 sej/$) = 3573 em$ha/yr (3285 ha) = 1.17E+7 em$/yr
3. Palm forest: (5.32E+15 sej/ha/yr) / (1.64E+12 sej/$) = 3235 em$ha/yr (1914 ha) = 6.19E+6 em$/yr
4. Tabonuco: (4.31E+15 sej/ha/yr) / (1.64E+12 sej/$) = 2621 em$ha/yr (5657 ha) = 1.48E+7 em$/yr
5. LEF total: weighted mean based on per hectare stream vol. and area of each forest type.

(a) Gravitational potential energy



(b) Chemical potential energy

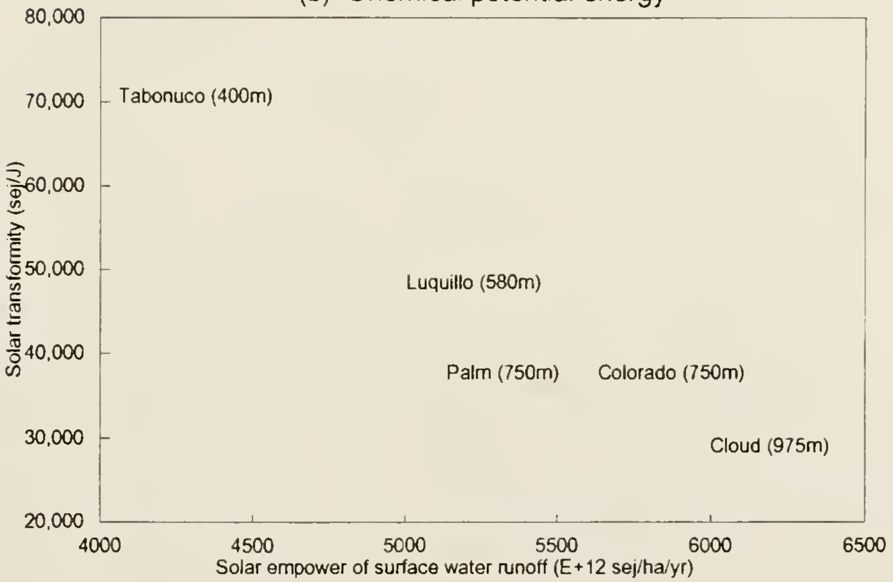


Figure 48. Solar transformity of surface water runoff as a function of empower for elevational forest watersheds of Luquillo Experimental Forest, Puerto Rico: (a) gravitational potential energy; and (b) chemical potential energy. (Luquillo = weighted mean for elevational systems).

Summary and Conclusions

Analyses of agroforest production and utilization systems undertaken in this dissertation suggest limits of biomass as a primary source of energy for civilization. The following conclusions are synthesized from this study.

- Natural ecosystems generally had lower transformities for above ground production and biomass storage than managed systems.
- Agroforest systems with longer rotations required less economic source inputs than intensively managed short-rotation systems resulting in higher net yields.
- Emergy investments per unit harvested biomass in managed, single species plantations were lower than in older and natural forests due to management efforts which reduced competition and facilitated removal.
- Increased management efforts, technological advances and economic subsidies may act to increase production efficiencies, thereby lowering transformities but the tradeoff of lowered net yields may outweigh the investments.
- Net emergy yield ratios for biomass production systems are time dependent because the environmental energy sources of available sun and rainfall are flow limited resulting in larger net yields delivered from systems with longer cycle times.
- Preparation and combustion of woodfuels require greater processing than fossil carbon fuels and thus deliver lower net yields per unit economic input. Electricity generated from nonrenewable fuels had greater net yields per unit economic investment than wood-fired electricity.
- Even under long rotations, biomass production systems cannot deliver high enough net yields to currently compete with existing supplies of nonrenewable sources because of the additional processing steps required to upgrade biomass.
- Because of the additional processing steps involved in development of biomass fuels, it is possible that primary fuels with high net emergy yield ratios emit lower CO_2 levels per unit available energy combusted if indirect emissions are considered.

- If nonrenewable energy sources become limiting in the future and sources with low net yields are all that are available, forest systems of long rotations may again become prominent and economic activity will have to be rescaled to fit a pattern of production based on flow-limited renewable energy sources.

- Cutting old growth forests for fuelwood, although net emergy may be as high as current primary fuels, is not sustainable because consumption would far exceed production rates.

- Direct timber extraction fails to recognize other ecosystem services such as water supply, wildlife habitat, and nonconsumptive uses such as tourism and research whose multiple benefits may be greater than the harvest.

- Because of the aforementioned limits imposed on biomass production systems and the general unavailability of suitable agroforestry lands, shifting to renewable sources of energy will require a general slowing of global economic activity and setting new and lower carrying capacities for human settlements.

- If fossil fuels currently make up half of the annual global emergy budget, and should they run out, civilization at the present standard of living would have to curtailed by half its current population and perhaps more considering the limits of solar conversions by general photosynthesis.

Forests will play an increasingly important role in a future of limited and declining energy sources. Optimal use of forests requires a comprehensive understanding of all co-products and ecosystem related services. By using emergy as a measure of contribution, multiple benefits were evaluated in this study on a common basis. It is suggested that public policy can be directed toward maximum emergy production and use, and that resource-use decisions including primary energy choices can be selected that deliver the greatest net emergy. Evaluations undertaken here suggest that forests and other solar energy-based biomass production systems offer multiple benefits to combined ecologic-economic systems at regional and global scales.

APPENDIX A

BASIC program to simulate model of cycle time and emergy yield ratio (Figure 41).

```
1     REM filename:  YR-CT.BAS (Emergy yield ratio and cycle time)
2     OPEN "b:\YR-CT1.PRN" FOR OUTPUT AS #1
3     SCREEN 1, 1: COLOR 0, 1
4     LINE (0, 0)-(310, 180), 3, B
5     LINE (0, 90)-(310, 90), 3, B
6     REM Scaling Factors:
7     t0 = 1
8     ct0 = 1
9     I0 = 1
10    R0 = 1
11    Q0 = 40
12    Y10 = 5
13    StY10 = 140
14    StY20 = 100
15    YR10 = 50
16    YR20 = 1
17    Y20 = 1
18    dt = .1
19    ct = 10
20    REM  Initial conditions:
21    Q = 25:  REM 1% avg. above ground biomass (120.3 ton/ha); E+9 J/ha
22    StQ = 4000
23    EmQ = StQ * Q
24    TEmF1 = 1
25    YR1 = 1
26    YR2 = 1
27    H = 1:  REM Harvest switch
28    REM Sources:
29    J = 40:  REM chemical potential in rain (0.8 m/yr); E+9 J/ha/yr
30    F = .66:  REM Fossil fuel inputs (F1 + F2 = 1.7 l/ha/yr + 16.9 l/ha/yr); E+9 J/ha/yr
31    StI = 18200:  REM Solar transformity for chemical potential energy in water; sej/J
32    StF = 40000:  REM Solar transformity for typical fuel; sej/J
33    REM Coefficients:
34    k0 = .000606
35    k1 = .015152
36    K2 = 1.5152E-05
37    k4 = .1678
38    k5 = 1.82E-06
39    k6 = 3.6364E-04
40    k7 = 3
42    PSET (t / t0, 180 - Q / Q0), 1
43    PSET (t / t0, 180 - Y1 / Y10), 3
44    PSET (t / t0, 90 - YR1 / YR10), 2
45    PSET (t / t0, 90 - YR2 / YR20), 5
```

```
46  REM Equations:
47  I = k0 * R * Q * F:  REM Environmental power inflow
48  F1 = k5 * R * Q * F * H: REM Silviculture feedback
49  F2 = K6 * Q * F * H:  REM Harvest feedback
50  GP = k1 * R * Q * F:  REM Gross production
51  Y1 = k1 * R * Q * F - K2 * R * Q * F - k4 * Q: REM Net production
52  Y2 = k7 * Q * F * H: REM Harvested biomass
53  R = J / (1 + k0 * Q * F):  REM Environ. input remainder
54  StQ = EmQ / Q
55  EmI = StI * (k0 * R * Q * F)
56  EmF1 = StF * F1
57  EmF2 = StF * F2
58  EmGP = EmI + EmF1
59  StGP = (EmGP) / (k1 * R * Q * F)
60  StY1 = (EmI + EmF1) / Y1
61  StY2 = (EmI + EmF1 + EmF2) / Y2
62  IF dQ > .05 THEN EmY1 = EmGP
63  IF dQ < .05 THEN EmY1 = 0
64  EmY2 = StQ * Y2
65  dQ = k1 * R * Q * F - K2 * R * Q * F - k4 * Q - k7 * Q * F * H
66  IF dQ > 0 THEN dEmQ = EmGP - EmY2
67  IF dQ = 0 THEN dEmQ = 0
68  IF dQ < 0 THEN dEmQ = StQ * dQ
69  Q = Q + dQ * dt
70  EmQ = EmQ + dEmQ * dt
71  REM TEm = sums emergy of pathway with time
72  TEmY2 = TEmY2 + EmY2 * dt
73  TEmY1 = TEmY1 + EmY1 * dt
74  TEmF1 = TEmF1 + EmF1
75  TEmF2 = TEmF2 + EmF1 + EmF2
76  YR1 = TEmY1 / TEmF1
77  YR2 = TEmY2 / TEmF2
78  t = t + dt
79  Y = Y + dt
80  IF Y >= 1 THEN H = .00001
81  IF Y > ct THEN H = 1: Y = 0
82  WRITE #1, ct, Q, Y1, Y2, YR1, YR2
83  IF t / t0 < 1200 GOTO 46
84  t = 1
85  ct = ct + 10:  REM Recalculates program for cycle times of 10 year intervals.
86  IF ct / ct0 < 360 GOTO 20
END
```

APPENDIX B

BASIC program model relating emergy yield and investment ratios (Figure 45).

```
1     REM filename:  YR-IR.BAS (Emergy yield ratio and investment ratio)
2     OPEN "b:\YR-IR.PRN" FOR OUTPUT AS #1
3     SCREEN 1, 1: COLOR 0, 1
4     LINE (0, 0)-(300, 180), , B
5     REM Sources and starting conditions:
6     J = 100
7     F = 1
8     StI = 1000
9     StF = 1000
10    k0 = .09:  REM 90% used when F = 100
11    k1 = .001:  REM Output of 1 when F = 100 and R = 10
12    REM Scaling
13    YR0 = .1
14    dF = .1
15    StY0 = 5000
16    IR0 = .01
17    F0 = 3
18    REM Equations
19    R = J / (1 + k0 * F)
20    I = k0 * R * F
21    Y = k1 * R * F
22    EmI = StI * I
23    EmF = StF * F
24    EmY = EmF + EmI
25    YR = EmY / EmF
26    IR = EmF / EmI
27    StY = EmY / Y
28    REM Sets X,Y coordinates for monitor display:
29    PSET (IR / IR0, 180 - YR / YR0)
30    PSET (IR / IR0, 180 - StY / StY0)
31    WRITE #1, IR, YR, StY
32    F = F + dF
33    IF IR / IR0 < 240 GOTO 18
END
```

LITERATURE CITED

Anonymous. 1976. Wood for structural and architectural purposes. Wood and Fiber. 8:49.

Birdsey, R.A. and P.L. Weaver. 1982. The forest resources of Puerto Rico. U.S. Dept. of Agric. Forest Service Resource Bulletin, SO-85. Southern Forest Experiment Station, New Orleans, LA. 59 pp.

Birdsey, R.A. and P.L. Weaver. 1987. Forest area trends in Puerto Rico. Research note SO-331, USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA. 4 pp.

Boltzmann, L. 1905. Der zweite haupsatz der mechanishen warme. Theorietical Almanach der K. Acad. Wiss. Mechanishe, Wien, 36: 255-299.

Boyles, D.T. 1984. Bio-Energy: Technology, Thermodynamics and Costs. Ellis Horwood Ltd., Chichester, England. 158 pp.

Brown, M.T. and R.A. Herendeen. 1995. Embodied energy analysis and emergy analysis: A comparative view. In press, J. Ecol. Econ.

Brown, M.T. and T.R. McClanahan. 1992. Emergy analysis perspectives of Thailand and Mekong River Dam Proposals. Final Report to The Cousteau Society. Center for Wetlands publication, Univ. Fla., Gainesville.

Brown, M.T., H.T. Odum, G. McGrane, R.D. Woithe, S. Lopez, and S. Bastianoni. 1995. Emergy evaluation of energy policies for Florida. Final Report to the Florida Energy Office. Center for Environmental Policy, Dept. Env. Eng. Sci., Univ. Fla., Gainesville.

Brown, M.T., R.D. Woithe, H.T. Odum, C. Montigue, ad E.C. Odum. 1993. Emergy analysis perspectives of the Exxon Valdez Oil Spill in Prince William Soud Alaska. Ctr. Wetlands and Water Resources publ., Univ. Fla., Gainesville. 142 pp.

Brown, S. and A.E. Lugo. 1984. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica 14(3): 161-187.

Brown, S. and A.E. Lugo. 1990. Tropical secondary forests. J. of Tropical Ecology 6:1-32.

Brown, S., A.E. Lugo, S. Silander, and L. Liegel. 1983. Research history and opportunities in the Luquillo Experimental Forest. Gen. Tech. Rep. SO-44. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA. 128 pp.

Bullard, C.W., P.S. Penner, and D.A. Pilati. 1978. Net energy analysis: Handbook for combining process and input-output analysis. Resources and Energy 1: 267-343.

Caribbean National Forest. 1992. Draft forest management plan - 1992. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA.

Chinea-Rivera, J.D. 1992. Invasion dynamics of the exotic legume tree *Albizia procera* (Roxb.) Benth. in Puerto Rico. Ph.D. dissertation, Cornell University, Ithaca, NY. 113 pp.

Comar, V. 1993. An emergy evaluation of the central Amazon town of Itacoatiara, its plywood and veneer industry and the floodplain of the Madeira River basin. M.S. Thesis, National Institute for Amazon Research and Unviersity of Amazonas, Brazil. 148 pp.

Cook, E. 1976. Man, energy and society. W.H. Freeman, San Francisco, CA.

Costanza, R. 1980. Embodied energy and economic valuation. Science 210: 1219-1224.

Cropper, W.P., Jr., and K.C. Ewel. 1983. Computer simulation of long-term carbon storage patterns in Florida slash pine plantations. For. Ecol. Manage. 6: 101-114.

Davidson, J. 1984. Forestry in Papua New Guinea: A case study of the Gogol woodchip project near Madang. In: L.S. Hamilton (ed.) Forest and Watershed Development and Conservation in Asia and the Pacific. Westview Press, Inc., Boulder, CO. pp. 19-138.

DeAngelis, D.L., R.H. Gardner, and H.H. Shugart, Jr. 1981. Productivity of forest ecosystems studied during IBP: the woodlands data set. In: D.E. Reichle (ed.) Dynamic Properties of Forest Ecosystems--International Biol. Prog. 23. Campbridge Univ. Press, New York. pp. 567-672.

Dissmeyer, G.E. 1983. Sound soil and water management is good economics. In: E.L. Stone (ed.) The managed slash pine ecosystem: Proc. of symposium. Sch. Forest Res. and Conservation, Univ. Fla., Gainesville. June 9-11. 434 pp.

Doherty, S.J. and M.T. Brown (eds.). 1992. Emergy analysis perspectives, sustainable development and public policy options for Papua New Guinea. Final report to the Cousteau Society. Ctr. for Wetlands publication 93-06, Univ. Fla., Gainesville.

Doherty, S.J., P.O. Nilsson, and H.T. Odum. 1993. Emergy analysis of forest production and industries in Sweden. Final report to Vattenfall (Swedish Energy Board) and the Royal Academy of Agricultural Science. Swedish Univ. of Agricultural Sci., Garpenberg, Sweden. 107 pp.

Doherty, S.J., F.N. Scatena, and H.T. Odum. 1994. Emergy evaluation of the Luquillo Experimental Forest and Puerto Rico. Final Report to the International Institute of Tropical Forestry, U.S.D.A. Forest Service, Rio Piedras, PR. 75 pp.

Eriksson, B. and H. Odin. 1990. Climate. In: Nilsson, N-E (ed.) The Forests: National Atlas of Sweden. National Board of Forestry, SNA, Italy. pp. 34-37.

Ewel, J.J. and J.L. Whitmore. 1973. The ecological life zones of Puerto Rico and the U.S. Virgin Islands. USDA Forest Service Research Paper ITF-18, Rio Piedras, PR. 72 pp.

Ewel, K.C. 1991. A simulation model of the role of belowground dynamics in a Florida pine plantation. Forest Science. 37(2): 397-438.

Federal Energy Administration, U.S. Dept. Agriculture. 1976. Energy and U.S. agriculture: 1974 database FEA/D-76/459. U.S. Government Printing Office, Wash., DC. 260 pp.

Fluck, R.C. 1981. Net energy sequestered in agricultural labor. Transactions of the Am. Soc. Agric. Eng. 24(6): 1449-1455.

Fluck, R.C., S.P. Balwinder, and C.D. Baird. 1992. Florida agricultural energy consumption model. Florida Energy Extension Service, IFAS, Univ. Fla., Gainesville. 34 pp.

Gardner, G. 1977. Comparison of energy analysis of oil shale. In: H.T. Odum and J.F. Alexander (eds.) Energy analysis models of the United States. Report to the U.S. Dept. of Energy, Ctr. for Wetlands, Univ. Fla., Gainesville. pp. 196-232.

Georgescu-Roegen, N. 1971. The Entropy Law and the Economic Process. Harvard Univ. Press, Cambridge, MA. 457 pp.

Gholz, H.L., L.C. Hendry, and W.P. Cropper, Jr. 1986. Organic matter dynamics of fine roots in plantations of slash pine (*Pinus elliottii*) in north Florida. Can. J. For. Res. 16: 529-538.

Gilliland, M.W. 1978. Energy analysis and public policy. Science 189: 1051-1056.

Hall, C. A. S., C. J. Cleveland, and R. Kaufmann. 1986. Energy and Resource Quality: The Ecology of the Economic Process. John Wiley & Sons, Inc., New York. 577 pp.

Hannon, B. 1973. An energy standard of value. Ann. Am. Acad. Polit. Soc. Sci. 410: 139-153.

Herendeen, R.A. 1981. Energy intensities in ecological and economic systems. J. Theor. Biol. 91:607-620.

Herendeen, R.A. and S. Brown. 1987. A comparative analysis of net energy form woody biomass. Energy 12(1): 75-84.

Herendeen, R.A. and C.W. Bullard. 1974. Energy costs of goods and services, 1963 and 1967. CAC Document no. 140. Center for Advanced Computation. Univ. of Illinois, Champaign-Urbana. 43 pp.

Hetz, E. and U. Sonesson. 1993. Energy analysis of reed canary grass for solid fuel and ley for biogas. The Swedish Univ. of Agric. Sciences, Research Notes no. 175. Garpenberg, Sweden. 14 pp.

IFIAS. 1974. Energy analysis workshop on methodology and conventions. International Fed. of Institutes for Advanced Study, Stockholm, Sweden. 89 pp.

Jansson, A.M. and J. Zucchetto. 1978. Energy, economic and ecological relationships for gotland, Sweden: A regional systems study. Ecological Bulletins No. 28. Natural Sci. Research Council, Stockholm, Sweden. 154 pp.

Jones, M.R. 1989. Analysis of the use of energy in agriculture--approaches and problems. Agric. Systems 29: 339-355.

Jordan, C.F. 1971. Productivity of a tropical rain forest and its relation to a world pattern of energy storage. J. Ecol. 59: 127-142.

Keeton, W.T. and J. Gould. 1993. Biological Science. W.W. Norton & Co., New York. 530 pp.

Keitt, T.H. 1991. Hierarchical organization of energy and information in a tropical rainforest ecosystem. M.S. Thesis, Univ. Fla., Gainesville. 69 pp.

Keller, P.A. 1992. Perspectives on interfacing paper mill wastewaters and wetlands. Master's Thesis, Univ. of Florida, Gainesville. 133 pp.

Kempe, G., and G. Von Segebaden. 1990. What do forests look like? In: Nilsson, N-E (ed.) The Forests: National Atlas of Sweden. National Board of Forestry, SNA, Italy. pp. 56-69.

King, R.J. 1991. Earth farm: Energy-based systems analysis. Unpublished report, Texas Dept. of Agriculture, Austin. 26 pp.

King, R.J. and J. Schmandt. 1991. Ecological economics of alternative transportation fuels. Report to the Texas State Dept. of Energy. L.B.J. School of Public Affairs, Univ. of Texas, Austin. 26 pp.

Leach, G. 1975. Net energy analysis--is it any use? Proc. Net Energy Analysis Workshop, Aug. 25-38. Inst. of Energy Studies, Stanford Univ., CA. pp. 332-344.

López, A.M. and K.G. Soderstrom. 1983. Insolation in Puerto Rico. Solar Engineering. pp. 70-75.

Lotka, A.J. 1922. Contribution to the energetics of evolution. Proc. Natl. Acad. Sci. 8: 147-155.

Loudon, B. 1989. Organized tours and the Caribbean National Forest. USDA Forest Service, Southern Station Report for the Caribbean National Forest and the Luquillo Experimental Forest, New Orleans, LA.

Lugo, A.E. 1986. Water and the ecosystems of the Luquillo Experimental Forest. Gen. Tech. Rep. SO-63. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA. 17 pp.

Lugo, A.E., J.A. Gonzalez-Liboy, B. Cintron, an K. Dugger. 1978. Structure, productivity and transpiration of a subtropical dry forest in Puerto Rico. Biotropica 10(4): 278-291.

Lugo, A.E. and F.N. Scatena. 1995. Ecosystem-level properties of the Luquillo Experimental Forest with emphasis on the tabonuco forest. In: A.E. Lugo and Lowe (eds.), Tropical Forests: Management and Ecology. Ecol. Studies, vol. 112. Springer-Verlag, New York. pp. 59-108.

Lunmark, J-E. 1990. Forest ecology. In: N-E Nilsson (ed.), The Forests: National Atlas of Sweden. National Board of Forestry, SNA, Italy. pp. 48-55.

Margalef, R. 1963. On certain unifying principles in ecology. The American Naturalist. 897: 357-373.

Marks, J. 1990. Wood powder: an upgraded wood fuel. The Swedish Univ. of Agricultural Sciences, Research Notes no. 182. Garpenberg, Sweden. 28 pp.

McPherson, G.E., D.J. Nowack and R.A. Rowntree. 1994. Chicago's urban forest ecosystem: results of the Chicago urban forest climate project. Gen. Tech. Rep. NE-186. U.S.D.A. Forest Service, Northeastern Forest Experiment Station, Radnor, PA. 201 pp.

Murphy, P.G. and A.E. Lugo. 1986. Structure and biomass of a subtropical dry forest in Puerto Rico. Biotropica 18(2): 89-96.

Murphy, P.G., A.E. Lugo, A.J. Murphy, and D.C. Nepstad. 1995. The dry forest of Puerto's south coast. In: A.E. Lugo and Lowe (eds.), Tropical Forests: Management and Ecology. Ecol. Studies, vol. 112. Springer-Verlag, New York pp. 178-209.

NEA/FEP. 1990. Dendro Thermal Power Programme of Thailand. Master Plan, vol. 1; Main Report. The National Energy Administration of Thailand, The Forestry Energy Production Group, and Swedforest Energikonsult AB, Sweden. 86 pp.

Nilsson, N-E (ed.). 1990. The Forests: National Atlas of Sweden. The National Board of Forestry, SNA, Italy. 144 pp.

NOAA. 1977. Climatological data--Florida. National Oceanic and Atmospheric Administration, National Climatic Ctr., Environ. Data Services, Asheville, NC.

NOAA. 1982. Climatological data--Florida. National Oceanic and Atmospheric Administration, National Climatic Ctr., Environ. Data Services, Asheville, NC.

Odum, H.T. 1967. Energetics of world food production. Ch. 3 in: The World Food Problem: A Report of the President's Science Advisory Committe. Vol. 3. The White House. U.S. Government Printing Office, Washington, DC. pp. 55-94.

Odum, H.T. 1970. An emerging view of the ecological system at El Verde. Chapter I-10 In: H.T. Odum and R.F. Pigeon (eds.), A tropical rainforest: A study of irradiation and ecology at El Verde, Puerto Rico. U.S. Atomic Energy Commission publ. TID-24270. pp. I-191 - I-289.

Odum, H.T. 1971. Environment, Power and Society. John Wiley & Sons, Inc., New York. 331 pp.

Odum, H.T. 1983. Systems Ecology: An Introduction. John Wiley & Sons, New York. 644 pp.

Odum, H.T. 1984. Energy analysis of the environmental role in agriculture. In:

Odum, H.T. 1988. Self-organization, transformity, and information. Science 242: 1132-1139.

Odum, H.T. 1995a. Environmental Accounting: Emergy and Decision Making. Manuscript, Center for Environmental Policy, Dept. Env. Eng. Sci., University of Florida. In press, John Wiley & Sons, Inc., New York. 416 pp.

Odum, H.T. 1995b. Tropical forest systems and the human economy. In: A.E. Lugo and Lowe (eds.), Tropical Forests: Management and Ecology. Ecol. Studies, vol. 112. Springer-Verlag, New York. pp. 343-396.

Odum, H.T. and J.E. Arding. 1991. Emergy analysis of shrimp mariculture in Ecuador. U.S. A.I.D. working paper for Coastal Resources Center, University of Rhode Island, Narrangansett, RI. 114 pp.

Odum, H. T., M. T. Brown, and R. A. Christianson. 1986. Energy systems overview of the Amazon Basin. Report to The Cousteau Society. Center for Wetlands publ. no. 86-1, Univ. Fla., Gainesville. 190 pp.

Odum, H.T., C. Klystra, J. Alexander, N. Sipe and P. Lem. 1976. Net energy analysis of alternatives for the United States. In: Middle and Long-term Energy Policies and Alternatives--Hearings of Sub-committee on Energy and Power, 94th Congress. Serial no. 94-63. U.S. Government Printing Office, Washington, D.C. pp. 258-302.

Odum, H.T. and E.C. Odum. 1979. Energy system of New Zealand and the use of embodied energy for evaluating benefits of international trade. In: Proc. of Energy Modelling Symposium, Techincal Publ. no. 7, N.Z. Ministry of Energy Wellington. 247 pp.

Odum, H.T. and E.C. Odum. 1983. Energy analysis overview of nations. Inter. Inst. for Applied Systems Analysis WP-83-82, Laxenburg, Austria. 366 pp.

Odum, H.T. and E.C. Odum. 1984. System of ethanol production from sugarcane in Brazil. Ciencia y Cultura 37(11): 1849-1855.

Odum, H.T., E.C. Odum, and M. Blissett. 1987. Ecology and economy: Emergy analysis and public policy in Texas. Lyndon B. Johnson School of Public Affairs. Policy Research Report no. 78. Office of Natural Resources and Texas Dept. of Agric., Austin, TX. 178 pp.

Odum, H.T. and R.C. Pinkerton. 1955. Time's speed regulator: The optimum efficiency for maximum power output in physical and biological systems. Am. Sci. 43: 321-343.

Ovington, J.D. and J.S. Olson. 1970. Biomass and chemical content of El Verde lower montane rain forest plants. Chapter H-2 in: H.T. Odum and R.F. Pigeon (eds.), A Tropical Rainforest: A Study of Irradiation and Ecology at El Verde, Puerto Rico. U.S. Atomic Energy Comm. publ. TID-24270. pp. H-53 - H-77.

Parrotta, J.A. 1987a. *Albizia lebbek* (L) Benth.: Siris. Silvics of forest trees of the American Tropics. USDA Forest Service publ. SO-ITF-7, Southern Forest Experiment Station, New Orleans, LA. 5 pp.

Parrotta, J.A. 1987b. The influence of density on stand development, biomass partioning and nutrient allocation in *Alibizia lebbek* (L) Benth. plantations in Puerto Rico. Ph.D. dissertation. Yale University, New Haven, CT. 210 pp.

Parrotta, J.A. 1993a. Assisted recovery of degraded tropical lands: Plantation forests and ecosystem stability. Chapter 15 in: M.G. Paoletti, W. Foissner and D. Coleman (eds.), Soil Biota, Nutrient Cycling, and Farming Systems. Lewis Publishers, Boca Raton, FL. pp. 169-182.

Parrotta, J.A. 1993b. Secondary forest regeneration on degraded tropical lands: The role of plantations as foster ecosystems. Chapter 6 in: H. Lieth and M. Lohmann (eds.), Restoration of Tropical Forest Ecosystems. Kluwer Academic Publ., Amsterdam, The Netherlands. pp. 63-73.

Peters, N., P. Knobloch and M. Ash. 1981. Energy losses and gains in energy production from forest wood residue. Inter. J. of Energy Systems 1(2): 166-169.

Pimentel. D., D. Nafus, W. Vergara, D. Papaj, L. Jaconetta, M. Wulfe, L. Olsvig, K. Frech, M. Loye, and E. Mendoza. 1978. Biological solar energy conservation and U.S. energy policy. BioScience 28(6): 376-381.

Pritchett, W.L. 1983. Nutition and fertilization of slash pine. In: E.L. Stone (ed.) The managed slash pine ecosystem: Proc. of symposium. Sch. Forest Res. and Conservation, Univ. Fla., Gainesville. June 9-11. 434 pp.

Reaven, S.J. 1986. Perspectives on convergence in net energy analysis. Proc. from Energy from Biomass and Wastes Symposium, Washington, DC. 14 pp.

Reyes, G., S. Brown, J. Chapman, and A.E. Lugo. 1992. Wood densities of tropical tree species. U.S.D.A. Forest Service General Tech. Report S0-88. Southern Forest Experiment Station, New Orleans, LA. 15 pp.

Scatena, F.N. 1990. Watershed scale rainfall interception on two forested watersheds in the Luquillo Mountains of Puerto Rico. Journal of Hydrology 113: 89-102.

Scienceman, D.M. 1987. Energy and emergy. In: G. Pillet and T. Murota (eds.) Environmental Economics--The Analysis of a Major Interface. Roland Leimgruber, Geneva. pp. 257-276.

Sedlik, B.R. 1978. Some theoretical considerations of net energy analysis. Proc. Energy Modeling and Net Energy Analysis Symposium, Institute of Natural Gas Technology, Chicago, IL. pp. 245-261.

Sennerby-Forsse, L. 1986. Handbook of energy forestry. Dept. of Ecology and Environmental Research, Swedish Univ. of Agr. Sci., Uppsala, Sweden. 29 pp.

Sheffield, J.T.. 1983. Slash pine resource. In: E.L. Stone (ed.) The managed slash pine ecosystem: Proc. of symposium. Sch. Forest Res. and Conservation, Univ. Fla., Gainesville. June 9-11. 434 pp.

Skogsstyrelsen. 1987. Swedish forest: facts about Swedish forestry and wood industries. B. Bernadotte and U. Gustafsson (eds.). Sweden National Board of Forestry, Jonkoping, Sweden. 111 pp.

Slesser, M. 1978. Energy in the Economy. St. Martin's Press, Macmillian, New York. 162 pp.

Slesser, M. 1984. Net energy analysis for biomass: State of the art. In: H. Egnéus and A Ellegård (eds.) Bioenergy Vol. 1. Elsevier Applied Science Publ., New York. pp. 19-38.

Slesser, M. 1987. Net energy as an energy planning tool. Energy Policy 228-238.

Smil, V. 1983. Biomass Energies: Resources, Links, Constraints. Plenum Press, New York. 453 pp.

Smil, V. 1991. General Energetics: Energy in the Biosphere and Civilization. John Wiley & Sons, Inc., New York. 369 pp.

Sonesson, U. 1993. Energy analysis of biofuels from winter wheat, rape seeed and salix. The Swedish Univ. of Agric. Sci., Research Notes no. 174. Uppsala, Sweden. 54 pp.

Spreng, D.T. 1978. On time, information, and energy conservation. Oak Ridge Associated Universities/Inst. Energy Anal. Report 78-22, Oak Ridge, TN.

Spreng, D.T. 1988. Net-Energy Analysis and the Energy Requirements of Energy Systems. Praeger Publ., New York. 289 pp.

Stanhill, G. 1983. Agricultural labour: An energy source or sink? Volcani Center publ. E. Institute of Soils and Water, ARO., Bet Dagan, Israel. 31 pp.

Strata, T.J. 1989. Costs and cost trends for forestry practices in the south. Forest Farmer Manual, 27th edition.

Sundberg, U., H. T. Odum, S. J. Doherty. 1991. 18th century charcoal production. The Swedish Univ. of Agric. Sci., Research Notes no. 212. Garpenberg. 10 pp.

Sundberg, U., and C.R. Silversides. 1988. Operational efficiency in forestry. Kluwer Academic Publ., Boston. 219 pp.

Swedish Power Association and Vattenfall. 1981. Hydropower in Sweden. The Swedish Power Assoc., Stockholm. 143 pp.

Vikinge, B. 1991. Forest thinning operations. In: S.J. Doherty, H.T. Odum and P.O. Nilsson (eds.) Emergy analysis: A biophysical bridging between the economies of humanity and nature. A report of initial studies to Vattenfall and the Royal Academy of Agricultural Sciences, Stockholm. 13 pp.

Wang, F.C., J. Richardson, K.C. Ewel, and E.T. Sullivan. 1981. Preliminiary energy analysis of utilizing woody biomass for fuel. In: W.J. Mitsch, R.W. Bosserman and J.M. Klopatek (eds.), Energy and Ecological Modelling. Elsevier Scientific Publ. Co., New York. pp. 673-680.

Weaver, P.L. 1972. Cloud moisture interception in the Luquillo Mountains of Puerto Rico. Carib. J. Sci. 12(3-4): 129-144.

Weaver, P.L., M.D. Byer, and D.L. Bruck. 1973. Transpiration rates in the Luquillo Mountains of Puerto Rico. Biotropica 5(2): 123-133.

Weaver, P.L. and P.G. Murphy. 1990. Forest structure and productivity in Puerto Rico's Luquillo Mountains. Biotropica 22(1): 69-82.

World Resources Institute. 1994. World Resources 1994-95: A Guide to the Global Environment--People and the Environment. Oxford University Press, New York. 400 pp.

BIOGRAPHICAL SKETCH

Steven Doherty was born in Oak Park, Illinois on July 21, 1962, and moved to Jacksonville, Florida, when he was eight years old. He attended Wolfson Sr. High, receiving his high school diploma in 1980.

As an undergraduate, Steven attended North Carolina State University and the University of Florida, receiving the Bachelors of Science degree in wildlife ecology in 1985 from the School of Forest Resources and Conservation at UF. Two years were spent as a biologist and community education instructor before returning to graduate school.

He completed concurrent masters degrees at UF in the Departments of Urban and Regional Planning and Environmental Engineering Sciences, receiving the Masters of Art degree in environmental planning in 1990 and a Masters of Science degree in systems ecology in 1991. During this time, he worked as a graduate research assistant for the Center for Wetlands at UF. Two years were spent as an associate research scientist at the University of Texas, Austin, with the Department of Zoology. He has taught as substitute school teacher, naturalist, community college instructor and has co-taught two graduate classes.

As part of his dissertation research, Steven spent six months in Garpenberg, Sweden, at the University of Agricultural Sciences and an additional six months in Rio Piedras, Puerto Rico, with the International Institute of Tropical Forestry. He graduated with a Doctor of Philosophy degree in 1995.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

H T Odum

H.T. Odum, Chair
Graduate Research Professor of
Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

J.J. Delfino
Professor of Environmental Engineering
Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

C. F. K

C.F. Kiker
Professor of Food and Resource Economics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

B.L. Capehart
Professor of Industrial and Systems
Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

MTBrown

M.T. Brown
Associate Scientist of Environmental
Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

F.N. Scatena

F.N. Scatena
Research Hydrologist, International
Institute of Tropical Forestry
Rio Piedras, Puerto Rico

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1995

Winfred M. Phillips
Dean, College of Engineering

Karen A. Holbrook
Dean, Graduate School

LD
1780
1995
.D655

UNIVERSITY OF FLORIDA
3 1262 08557 0645